CRANFIELD UNIVERSITY

MUFTAH EM. M. ZORGANI

Procedure for selecting appropriate steels for machine design

SCHOOL OF ENGINEERING

MSc THESIS

MSc BY RESEARCH
Academic Year: 2008 - 2009

Supervisor: Dr. R. H. Banister & Dr. D Mba.
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ABSTRACT

Selection of steels for industrial purposes usually means choosing a type of steel to make a part or a product. The steel that is chosen must meet all the designer requirements. A quantitative selection procedure has been used to analyze the large amount of data involved in this selection process so that a complete and systematic evaluation can be made.

The designer is responsible for the selection of steel, and this selection requires the designer to find data and information on the mechanical properties required, and also learns ways to improve these properties through different heat treatment processes.

When a large number of steels and a large number of specified mechanical properties are being evaluated for selection, the weighed properties method can require a large number of tedious and time-consuming calculations. In such cases a computer program could greatly facilitate the selection process.

This thesis reports the selection of steels for gears, shafts, fasteners and springs where the steps involved in the weighted properties method which is written in the form of a simple computer program to select steels from a data bank. This program also includes the digital logic method to help in determining weighing factors.

The steels are ranked according to standard designation; BS, AISI, and DIN. It has been found that alloyed steels hardened and tempered at 205^0C are most suitable for gears, shafts, fasteners, and springs when higher mechanical properties required, and carbon and low alloyed steels when cost is the main consideration.

Keywords:

Gears, shafts, fasteners, springs, performance index, relative importance

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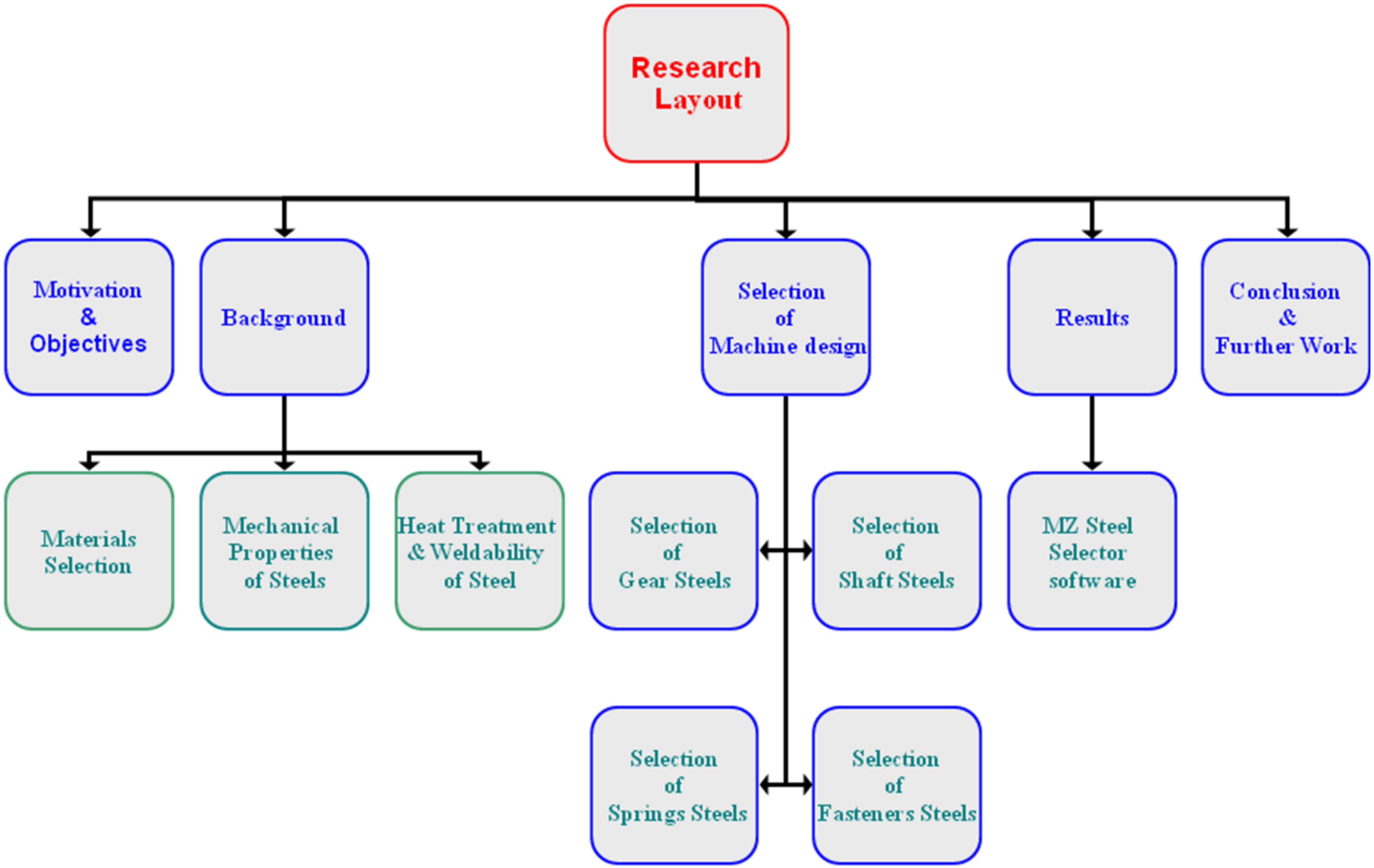

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Chapter 1

1 INTRODUCTION

The aim of material selection in manufacturing is to create products and components that perform properly under operating conditions. Due to advances in materials science, there is a wide array of available material. The increase in the number of choices has often led to improper or poor material selection. Sometimes, a more expensive alloy is chosen when a cheaper alloy would have been sufficient. The must important goals of the material selection are to:

- Minimizes the cost of manufacturing, by reducing the time spent in the design stage.
- Minimizes the cost of the material.
- Maximizes the performance of the product [1].

Most machines usually contain components that common to use, for example shafts, gears …etc. Any machine part must operate with the conditions set by the designer (pressure, temperature, loading rate, etc.), and early failure of it is an indication of the fact that the part is scrap (not made of the material, proper methods were not used, or serious errors in calculations of strength, etc., were allowed). A few materials are frequently used for these components, and the performance or functional requirements a material are expressed in terms of physical, mechanical, thermal, electrical, or chemical properties.

Steels are the most and reliable material can the designer used for most machine components. There are hundreds different type of steels, so the designer needs information about all of these steels, when, optimization is needed and the steel that is chosen must meet all the designer requirements.

In this study the tried to show that the most important properties of steels that the machine designer should understand them are mechanical properties such as tensile properties (yield strength, ultimate tensile strength, and Young's modulus ...etc), compression, shear, fatigue strength, hardness, and cost. The relative importance of each of these requirements depends on a particular design situation. Also, the heat treatment processes (annealing, normalizing, hardening, and surface treatment) that affects the mechanical properties of steel will be provided. All technical data for each steel will be set in a way that makes the designer reach it in accurately and fast.

The weighted properties method of selection is used when several properties should be taken into consideration. Each machine part requirement is assigned a certain weight depending on its importance to the function of the design. The individual weighted property of each steel is summed to give a steel performance index. The steel with the highest performance index is considered as the optimum for the application.

Visual basic software is used to assist designer to select the proper steel easily and accurate. By using the created steel selector software; designer can make steels ranking list according to relative importance of mechanical properties, and cost for each machine element.

Chapter 2

2 MECHANICAL PROPERTIES OF STEELS

2.1 Loading

Loading is the application of a force on an object. Any material component may be subjected to many different loading and the performance of the material depends on the load applied. There are five basic loading conditions, tension, compression, bending, shear and torsion. In a tension loading the two end sides of the material (component) pulled until the material fractured or elongated. Compression is the opposite where the material pressed together. Loading by bending involves applying a load in a manner that causes a material to curve and results in compressing the material on one side and stretching it on the other. Shear load is applied parallel to the plane that caused the material to one side of the plane to slide on this material to the other side of the plane. Torsion is the application of a force that causes rotation in a material, different type of loading is shown in figure (2.1).

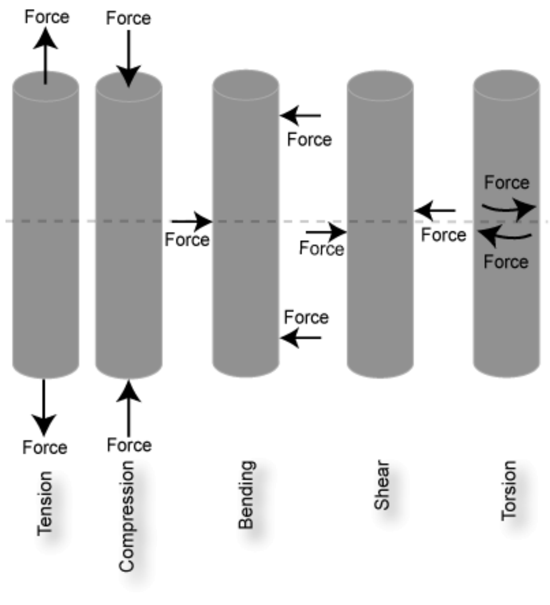


Figure 2-1 Type of loading [3]

When the applied load is constant it is called static loading and, if it is not fixed but fluctuate it is called dynamic (cycling) loading.

The mechanical properties of the materials are greatly affected by the loading type and method [3].

2.2 Stress and Strain

2.2.1 Stress

The stress is the applied force or system of forces that deform a material component and distributed in the material. Depending on the loading condition the distribution of the stresses will be uniform or not. For example a bar loaded in an axial tension will have a uniform tensile stress distribution. However a bending loaded bar will have a stresses distribution changes with distance perpendicular to the normal axis.

For example the stress in an axially loaded bar is equal to the applied force divided by the cross section area of the bar as shown in figure (2.2).

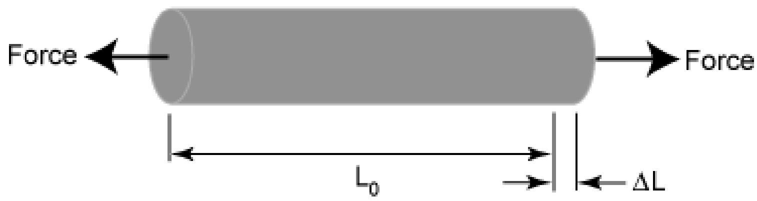


Figure 2-2 Generated by an axial loading [3]

$$\text{Stress}(\sigma) = \frac{F}{A_0} \quad \frac{N}{mm^2} \quad \text{MPa} \qquad \textbf{Equation 2-1}$$

Where the F is applied force, and A_0 is a cross section area [3].

2.2.2 Strain

Strain is the response of a material component to an applied stress. When a material component is exposed to a loading force a stresses will be produced which will lead to a material deformation. Engineering strain is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material and strain is a unit less number (inches per inch or meters per meter). Figure (2.3) shows the strain in a tension stretched bar which is the amount of elongation or change in length divided by the bar original length. As in the case of stress the strain distribution may or may not be uniform in a complex structural element depending on the nature of the loading condition.

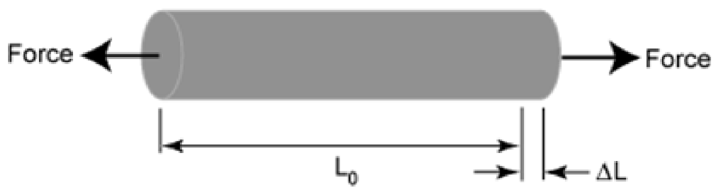


Figure 2-3 Strain garneted by an axial loading [3]

$$\text{Strain (e)} = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} \qquad \textbf{Equation 2-2}$$

Where ΔL is elongation, L_0 is original length, and L is measured length.

Small stress will cause a small amount of strain and the material will return to its original size after the stress is released (elastic deformation) and it returns to its unstressed state. Elastic deformation only occurs in a material when stresses are lower than a critical stress called the yield strength. If a material is loaded beyond it elastic limit, the material will remain in a deformed condition after the load is removed. This is called plastic deformation [4].

2.2.3 Stress concentration

When an axial load is applied to of a uniform cross section material component the stress will be distributed uniformly in the component cross section, but when a hole is made (drilled) in the material the stress distribution will not be a uniform, and the stress will be rearranged (redistributed) because of removed material from the component (hole), and the highest stresses will be at the edge of the hole. This phenomenon is known as stress concentration as shown in figure (2.4) [3].

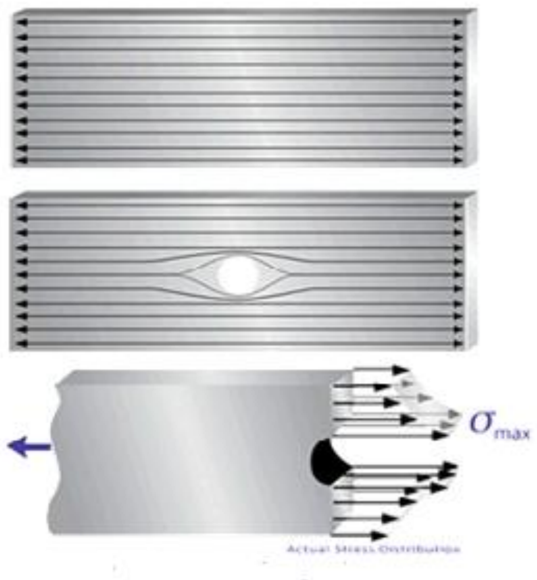


Figure 2-4 Stress concentration due to a hole [3]

2.3 Tensile test

A tensile test is a mechanical test where a specified specimen is loaded in then the applied load and the elongation of the specimen are measured. Many of mechanical properties are determined by tensile test such as modulus of elasticity, elastic limit, elongation, proportional limit, and reduction in area, tensile strength, yield strength and toughness.

A load versus elongation curve is obtained from the tensile test is which is then converted into a stress versus strain curve by using a specific equations (Eq.2.1 and Eq. 2.2). The load vs. elongation curve will have the same shape as the engineering stress vs. strain curve and each material has its own unique stress-strain curve. A typical engineering stress-strain curve is shown in figure (2.5) [5].

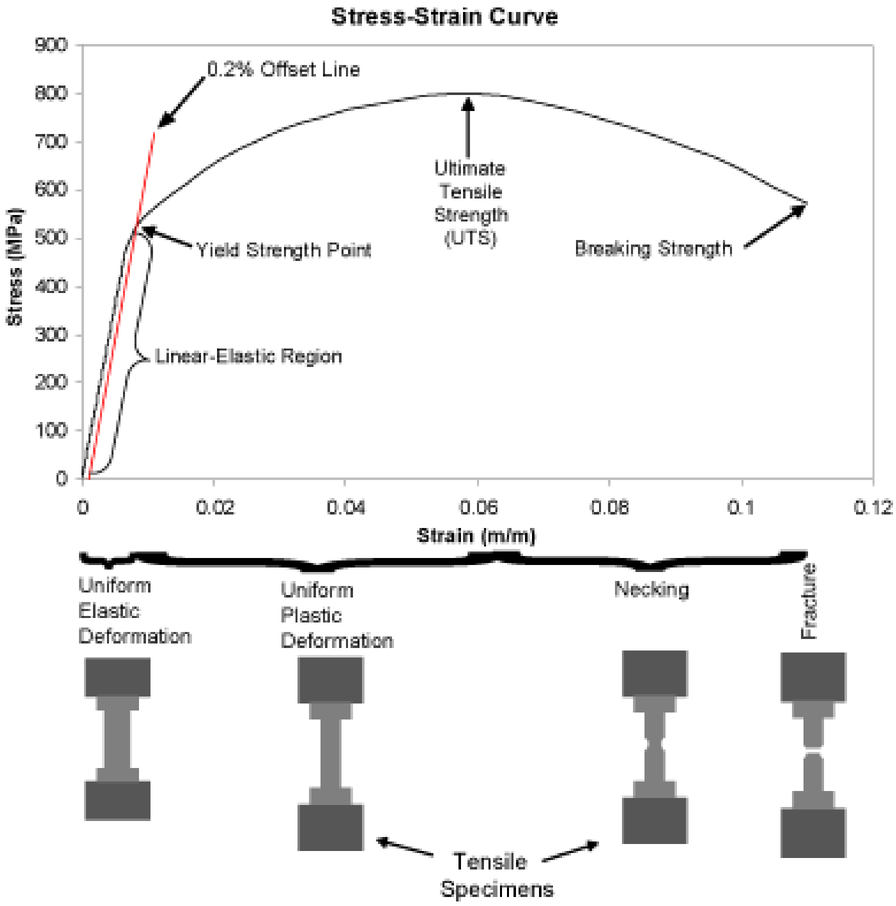
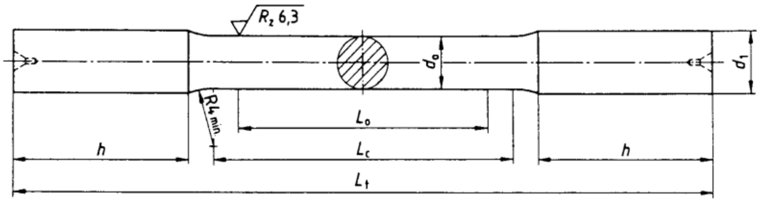


Figure 2-5 typical stress-strain curves for ductile materials [3]

2.3.1 Tensile test specimen

There are many standards test specimens for tensile test depending on the shape of the material component need to test. Figure (2.6) shows different specimen types according to DIN 50135 [6].



d_0 diameter of specimen

L_0 gauge length ($L_0 = r\ d_0$)

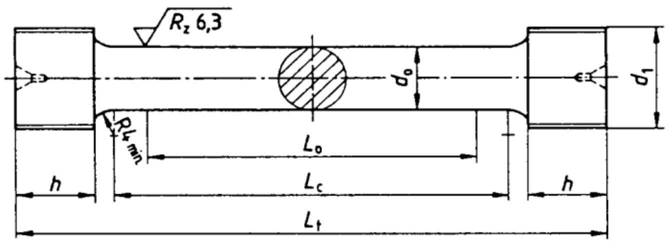
d1 diameter of grip (≈ 1,2 d_0)

L_c parallel length ($L_c \geq L_0 + d_0$)

h height of grip

L_t total length

(a)



d_0 diameter of specimen

L_0 gauge length ($L_0 = r\ d_0$)

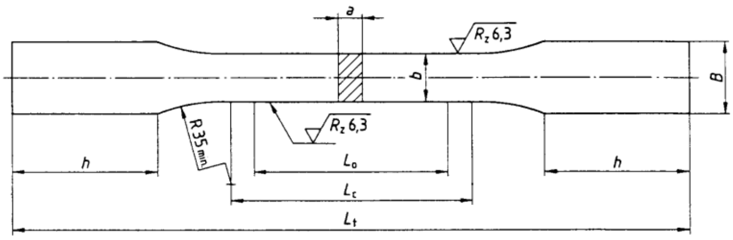
d1 diameter of grip (≈ 1,2 d_0)

L_c parallel length ($L_c \geq L_0 + d_0$)

h height of grip

L_t total length

(b)



a thickness of specimen

L_0 gauge length ($L_0 = r\ d_0$)

b width of specimen

L_c parallel length ($L_c \geq L_0 + d_0$)

B width of grip

L_t total length

h height of grip

(c)

Figure 2-6 Tensile test specimens according to Din standard 50135 (a) type A, (b) type B, and (c) type E [6]

2.3.2 Ductile materials

Ductile materials (most metals such as steels) generally exhibit a very linear stress–strain relationship up to a yield point. The linear line of the curve is the elastic deformation region and the slope is the modulus of elasticity (Young's Modulus). After the yield point the curve typically decreases slightly as the deformation continues the stress increases due to strain hardening (work hardening) until it reaches the ultimate strength (UTS). Until this point the specimen cross section area decreases uniformly due to Poisson's ratio (Poisson contractions). After this point a sharp decreases in cross section area in the middle of specimen will be observed (Necking). Eventually the neck becomes unstable and the specimen will be ruptured as shown in figure (2.7) [6].

2.3.3 Brittle materials

Brittle materials such as cast iron and concrete do not have yield point, and do not strain harden this will lead that the ultimate strength and breaking strength will be in the same point (no necking) as shown in figure (2.7). Typical brittle materials such as glass do not have any plastic deformation but fail while the deformation is elastic. A typical stress strain curve for a brittle material will be linear.

In brittle materials tensile strength is negligible compared to the compressive strength for many engineering applications. The fracture surface in these materials will be smooth and bright. And many materail fractured in mixed mode between ductile and brittle behavior figure (2.8) [6].

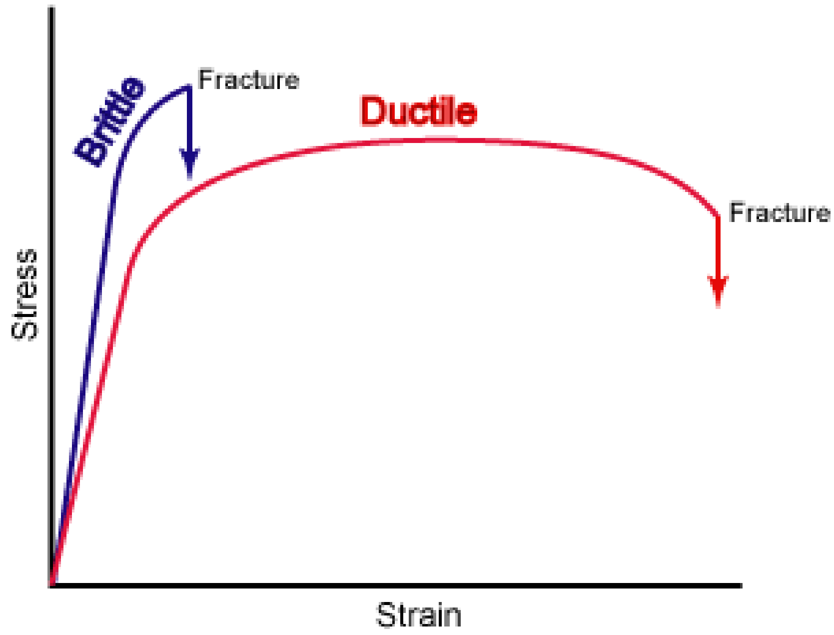


Figure 2-7Tension test for ductile and brittle material [3]

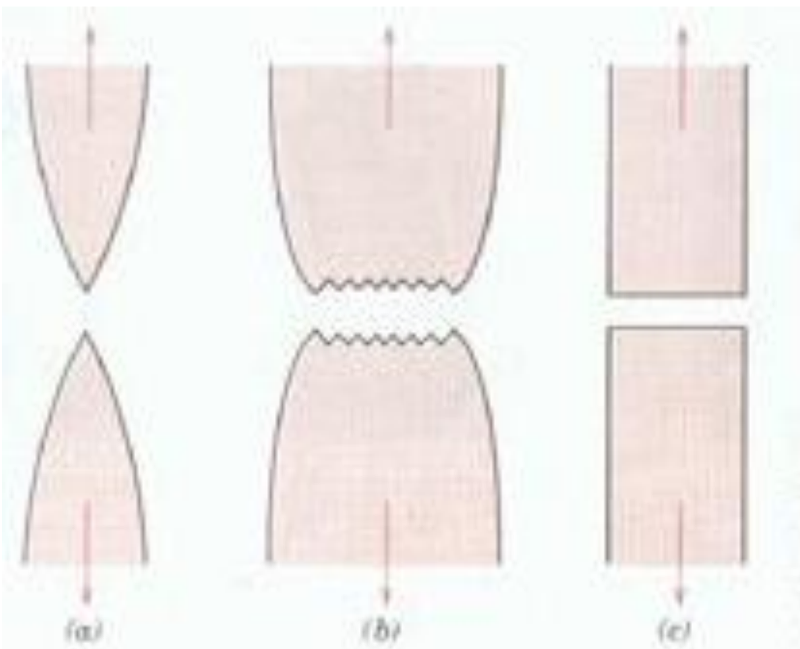


Figure 2-8 Fracture shape ductile cap – cone (right), mixed shear (middle), and brittle (left) [3]

2.3.4 Yield strength (σ_Y)

The stress at which material strain changes from elastic deformation to plastic deformation, causing it to deform permanently, in the brittle materials, it's difficult to define the yield point, and so proof stress will be considered [6].

2.3.5 Proof stress (offset yield stress)

In brittle material (non-linear deformation), the yield point difficult to appear in the stress- strain curve, so normally, the 0.2 % proof

Strength (Rp0.2) is stated as the equivalent parameter to the tensile yield strength as shown in Fig (2.1) [6].

2.3.6 Ultimate Tensile Strength (σ_{UTS})

The maximum stress a material can withstand when subjected to tension, compression or shearing. It is the maximum stress on the stress-strain curve [6].

2.3.7 Breaking strength (σ_f)

The stress coordinates on the stress-strain curve at the point of rupture end on the preparation of the specimen and the temperature of the test environment and material [6].

2.3.8 Modulus of elasticity (Young's Modulus)

The modulus of elasticity determines the elastic deflection of steel under load and it's used in many stress and deflection calculations.

$$\text{Modulus of Elasticity (E)} = \frac{\Delta Stress}{\Delta Strain}$$ **Equation 2-3**

Where, E is the modulus of elasticity, Δ is different between two stress or strain points. The modules of elasticity are the slope of the elastic area of the stress-strain curve, which is the straight line below the proportional limit. The modulus of elasticity is a measure of the rigidity or stiffness of steel [6].

2.3.9 Poisson’s Ratio

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Tensile deformation is considered positive and compressive deformation is considered negative. The definition of Poisson's ratio contains a minus sign so that normal materials have a positive ratio. Poisson's ratio, also called Poisson ratio or the Poisson coefficient.

$$\text{Poisson's ratio } (\vartheta) = \frac{e_{trans}}{e_{longt}} \qquad \textbf{Equation 2-4}$$

Where, ϑ is the resulting Poisson's ratio, e_{trans} is transverse strain (negative for axial tension, positive for axial compression), and e_{longt} is axial strain (positive for axial tension, negative for axial compression) [6].

2.3.10 Measures of Ductility (Elongation and Reduction of Area)

The ductility of a material is a measure of the extent to which a material will deform before fracture. The amount of ductility is an important factor when considering forming operations such as rolling and extrusion. It also provides an indication of how visible overload damage to a component might become before the component fractures.

The conventional measure of ductility is the length change of the specimen at fracture (elongation) and the reduction of area at fracture. Both of these properties are obtained by putting the specimen back together after fracture and measuring the change in length and cross section area. Elongation is the change in axial length divided by the original length of the specimen (percentage) Eq. 2.5. Reduction of area is the change in cross sectional area divided by the original cross section area (percentage) Eq.2.6. This change is measured in the necked down region of the specimen.

$$\text{Elongation\%} = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} \times 100$$ **Equation 2-5**

$$\text{Reduction of area \%} = \frac{\Delta A}{A_0} = \frac{A_0 - A}{A_0} \times 100$$ **Equation 2-6**

Where A_0 is the original cross section area, and A is the measures cross section area after fracture [6].

2.3.11 Strain hardening (work hardening)

Strain hardening is strengthening of material by generating a plastic deformation which will lead to increase the dislocations in the structure (lattice) the large number of dislocations formed (saturated) will prevent new dislocations to develop (dislocations resistance) this resistance will strengthened the material. It is often the work hardening produced by the process which is form a metal in its final shape such as cold rolling and cold drawing or by process after final shape is produced (shot peeing process) [7] .

2.4 Toughness

Toughness is the ability of the steel to absorb energy until fracture. Toughness can be found by taking the area (i.e., by taking the integral) underneath the stress-strain curve figure (2.9) [5].

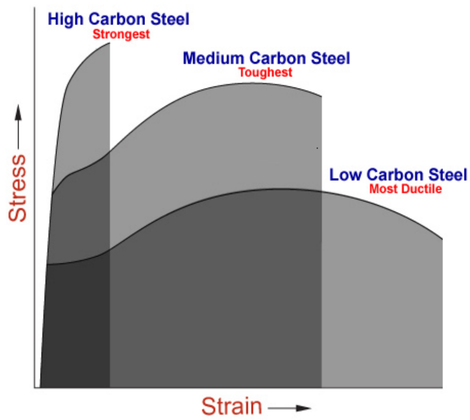


Figure 2-9 Toughness of different steels by integral the area under stress-strain curve [3]

2.5 Impact test

The impact test is applied a load at a very high rate of speed and uses specimens to make complex stress distribution. This combination of high strain rate and stress combination makes the impact test to evaluate the amount energy absorbed by the specimen material to fracture also impact test is used to determine the materials brittleness.

Impact test conducted on samples of notched standard specimens exposed to a shocked force to break it.

The value of energy absorbed to break the test sample is obtained from the test machine, and it will be a basis for impact resistance comparison between the materials.

There are several types of impact tests methods and the most used tests are Charpy and Izod tests where notched specimen is used and many testing machines can be used for both Charpy and Izod tests [6].

2.5.1 Charpy impact test

The standard specimen of the Charpy test is supported on both ends and is fractured by a sudden impact of a pendulum that strikes the middle of the sample on the un-notched side. Figure (2.10) shows the standard specimen and the impact force direction of Charpy test [6].

2.5.2 Izod impact test

Izod impact test uses a notched specimen which is similar to the Charpy specimen, but with different dimensions figure (2.11).

The main difference between two tests is that the specimen in Izod test is gripped at one end, and impact force will strike the specimen from the longest dimension. The advantage of this method is that many notches can be made in one specimen and the specimen can be also round shape, but there is disadvantage for this method that the time for fixing the specimen in the test machine will be longer this should be considered when the low temperature test will be done [6].

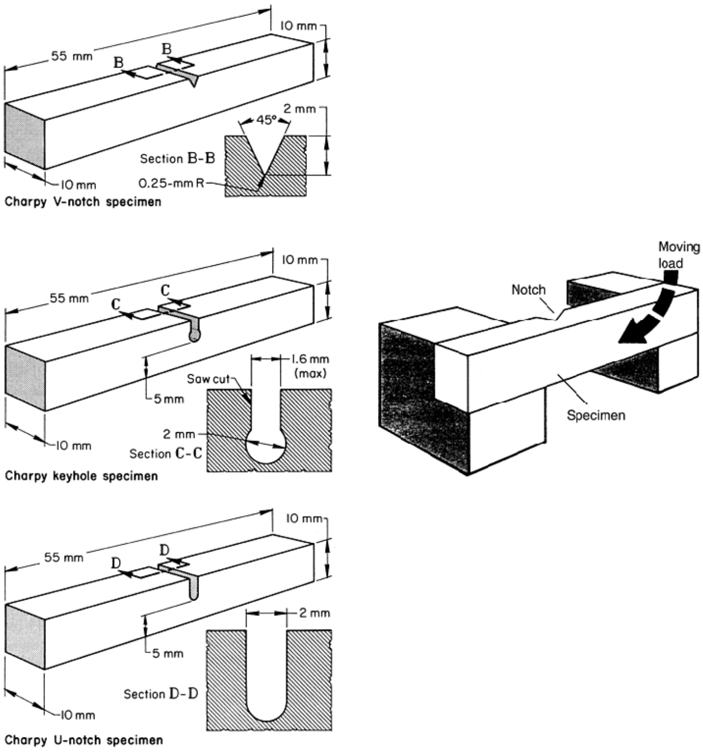


Figure 2-10 Standard specimen dimensions and direction of impact force of Charpy test [6]

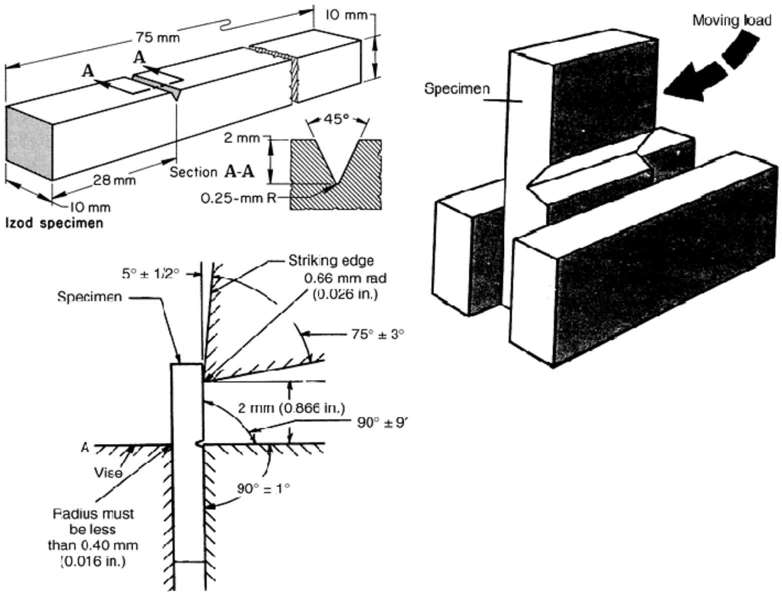


Figure 2-11 Standard specimen dimensions and direction of impact force of Izod test [6]

2.6 Compression test

Theoretically the compression test is the opposite of tension test (direction of loading) where during the test the shrinkage of a test specimen and displacement are recorded. Figure (2.12 left) shows the load deformation curve.

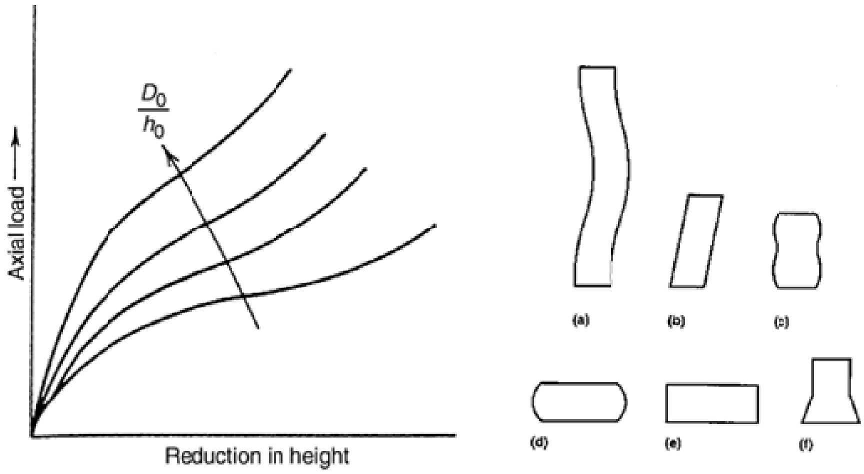


Figure 2-12 Load-deformation curves for compression tests with specimens having different initial values of *D*/*h* (left), and the modes of deformation in compression testing (right). [6]

The results obtained from compression test are similar to tensile test (compressive yield, compression ultimate stresses, and compression modulus of elasticity).

Compressive yield stress is measured in a same way to that done for tensile yield strength. Ultimate compressive strength is the stress required to rupture a specimen this value is much harder to determine for a compression test than it is for a tensile test since many material do not exhibit rapid fracture in compression. [4]

For some materials such as concrete the compressive strength is the most important material property that engineers use when designing and building a structure.

There are many modes of deformation in compression testing as shown in figure (2.12 right) where (a) Buckling when *L/D* > 5. (b) Shearing when *L/D* > 2.5. (c) Double barrelling when *L/D* > 2.0 and friction is present at the contact surfaces. (d) Barrelling when *L/D* < 2.0 and friction is present at the contact surfaces. (e) Homogenous compression when *L/D* < 2.0 and no friction are present at the contact surfaces. (f) Compressive instability due to work softening material [6].

2.7 Bending test

Bending test measures the flexibility (ductility) of the material. Conditions associated with bend tests shall apply to the specific forms or types of materials. For example, in some cases, specifications require that the material must be bent to specific degree. [7]

There are many types of bending test, such as wrap, wipe, V-block. The test tools (pins, mandrels, roller, and clamping devices) must be longer than specimen width and strong enough and rigid to resist.

In a Wrap bending test the bending force is applied by a roller that sweeps concentric around the bend radius figure (2.13 a).

Wipe bending forces are similar to wrap bending forces except that the bending force direction perpendicular to the clamped specimen and the required force is obtained by mandrel or roller figure (2.13 b).

V-block bending equipment consists of a mandrel and a bottom block or specimen supports. The specimen rests on supports or on the bottom block and is not clamped during the test and the bending force is applied in the middle of the specimen. The bending test is usually used to determining the material properties of welded parts (butt weld-fusion welded joints). The bending test is the cheapest and simplest method of testing the deformability of the weld joint the value of deformability is the bending angle of the stress applied at the first visible crack observed figure (2.13 c) [6] .

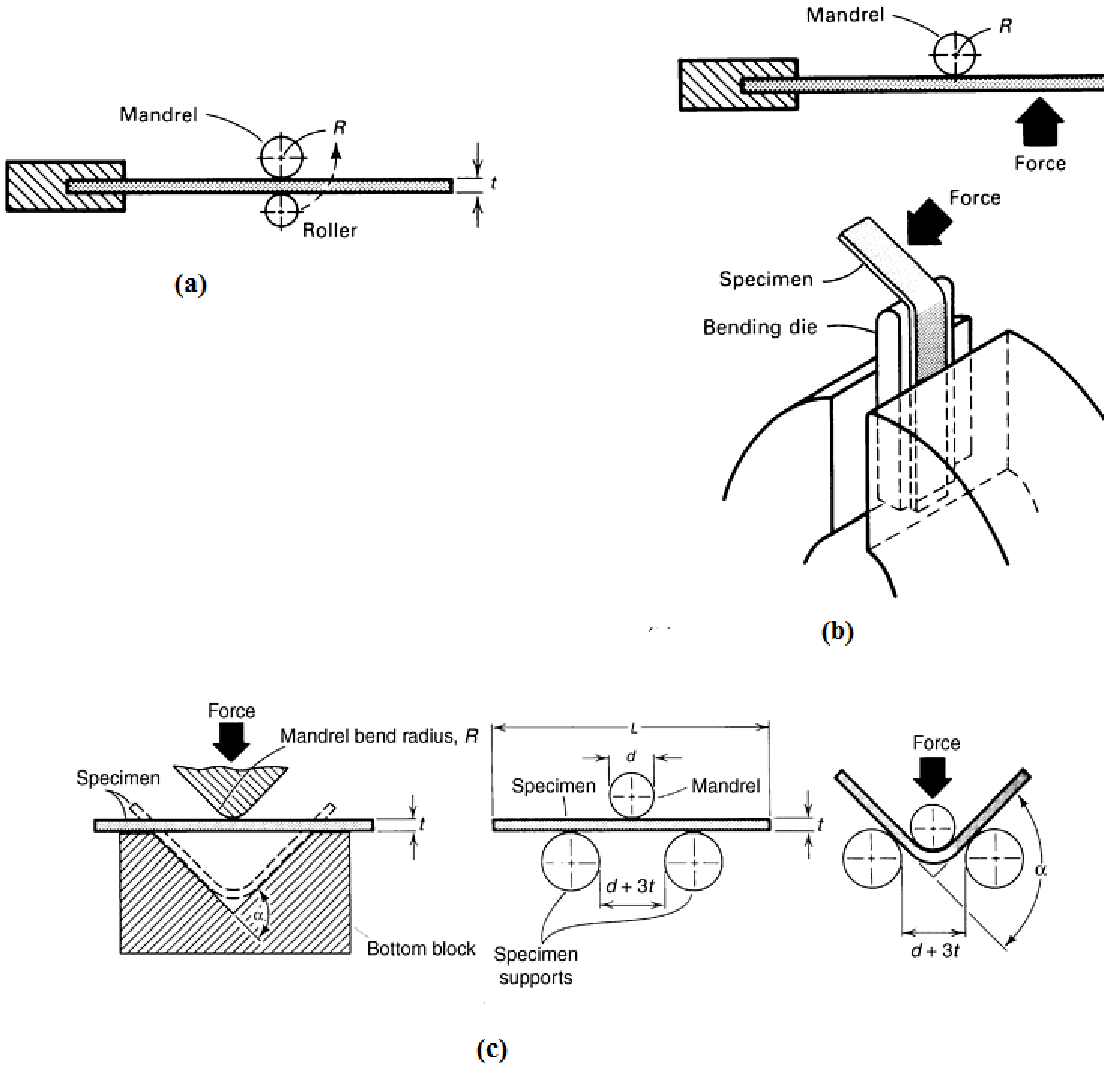


Figure 2-13 Bending test types (a) warp bending test , (b) Wipe bending test mandrel type with force applied near free end (upper), and die type with force applied V near free end (lower), (c) V-block bending devices closed V-block (right), and open -block (left) [6]

2.8 Fatigue test

Fatigue cracking is one of the primary damage mechanisms of structural components. Fatigue cracking results from cyclic stresses that are below the ultimate tensile stress or even the yield stress of the material.

The fatigue life of a component can be expressed as the number of loading cycles required to initiate a fatigue crack and to propagate the crack to critical size. Fatigue failure occurs in three stages crack initiation, stable crack growth (slow), and rapid fracture. In the second stage of fatigue some of the very small micro-cracks join together and begin to propagate through the material in a direction is perpendicular to the maximum tensile stress. Then the growth of one crack of the larger cracks will dominate over the rest of the cracks. With continued cyclic loading the growth of the dominate crack or cracks will continue until the remaining uncracked section of the component fractured. At this point the fracture toughness is exceeded and the remaining cross section of the material observed rapid fracture. This rapid overload fracture is the third stage of fatigue failure.

Many different fatigue testing machine are used depending on the type of loading (direct uniaxial loading, plane bending, and rotating beam loading). A uniaxial normal stress fatigue machine test is often used and other machines also used such as multiaxial fatigue loading (tensional, and bending).

Different testing specimens are used according to the test loading type. Figure (2.14) shows the fatigue machine test and the specimen test [7].

2.8.1 Endurance limit (Fatigue limit)

Endurance limit is the range of the fluctuated stress (cycle) which can be applied to the material without causing fatigue failure. Steels and titanium alloys have a distinct limit, amplitude below which there appears to be no number of cycles that will cause failure.

Other metals such as aluminium, copper, have no distinct limit, and will eventually fail even from small stress amplitudes, as shown in figure (2.15) [7] .

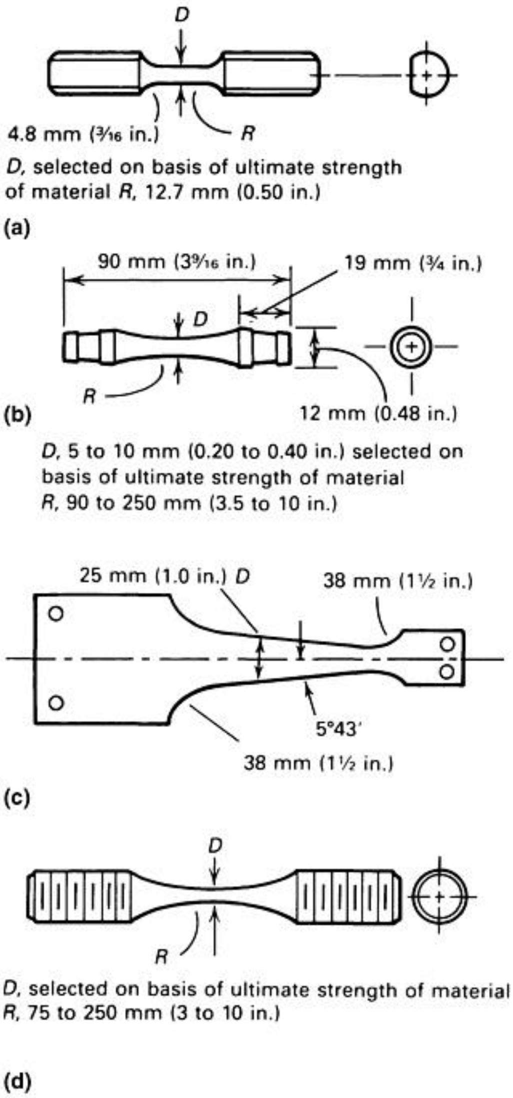


Figure 2-14 Fatigue test (left), types of test specimens (right), (a) Torsional specimen. (b) Rotating-beam specimen. (c) Plate specimen for cantilever reverses bending. (d) Axial loading specimen [6]

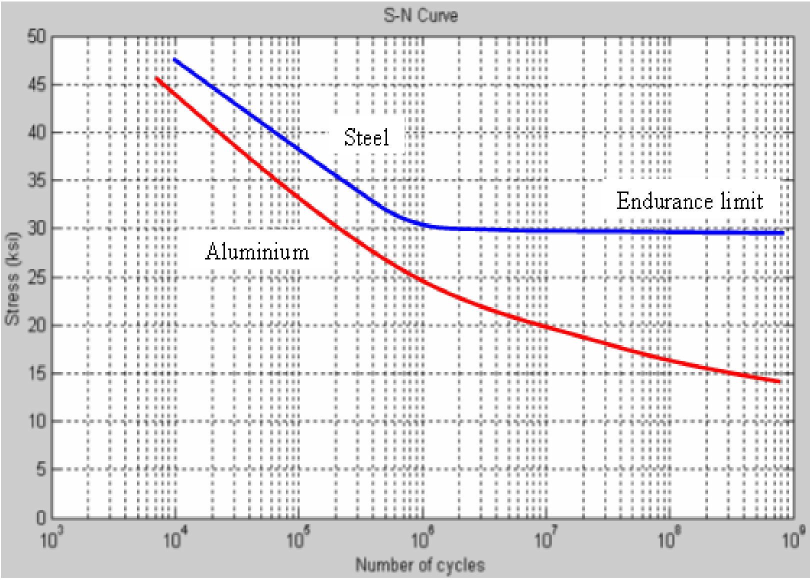


Figure 2-15 Curves of applied stress vs. number of cycles for steel (upper and showing an endurance limit) and aluminium (lower and showing no such limit). [3]

2.9 Shear test

A shearing stress acts parallel to the stress plane where a tensile is or compressive stress acts normal to the stress plane. Shear properties are used in the fastened components, webs, and torsion members. Shear properties are dependent on the type of shear test and there is a variety of different standard shear tests that can be performed including the single shear test, double shear test, blanking shear test, and torsion shear test. The shear modulus of elasticity is considered a basic shear property [7].

2.10 Hardness test

Hardness is the resistance of a material to localized deformation. The term can apply to deformation from indentation, scratching, cutting or bending. In metals, ceramics and most polymers, the deformation considered is plastic deformation of the surface.

Hardness measurements are widely used for the quality control of materials because they are quick and considered to be non-destructive. There are a large variety of methods used for determining the hardness of materials. The hardness is either determined by measuring the impression area occurred by force (Brinell and Vickers tests) or by measuring the impression depth occurred by testing force (Rockwell test).

2.10.1 Brinell hardness test

The oldest of the hardness test methods in common use on engineering materials is the Brinell hardness test.

It is carried out using a hardened steel ball (specified diameter) or a ball made from hard metal and can be applied for materials (specified load) up to a Brinell hardness of 450 HB. The Brinell hardness number is obtained by dividing the load used, in kilograms, by the measured surface area of the indentation, in square millimetres, left on the test surface figure (2.16).

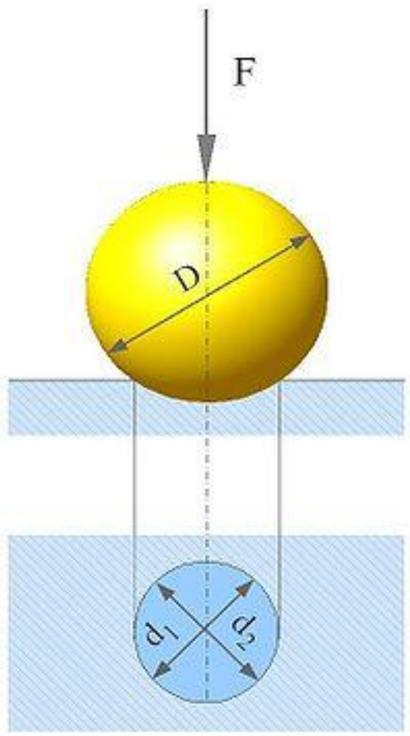


Figure 2-16 Brinell indentation [3]

$$\text{Brinall Hardness (HB)} = \frac{2P}{\pi D(D-\sqrt{D^2-d^2})} \qquad \textbf{Equation 2-7}$$

Where, P is the applied load (kg), D is a ball indenter diameter (mm), and d is an indentation diameter (mm). The Brinell test is frequently used to determine the hardness metal forgings and castings that have a large grain structures. The Brinell test provides a measurement over a fairly large area that is less affected by the course grain structure of these materials than are Rockwell or Vickers tests. Wide range of materials can be tested using a Brinell test by varying the test load and indenter ball size. Brinell testing is typically done on iron and steel castings using a 3000Kg test force and a 10mm diameter ball. A 1500 kilogram load is usually used for aluminium castings. Copper, brass and thin stock are frequently tested using a 500Kg test force and a 10 or 5mm ball. The test conditions should be reported along with the Brinell hardness number. A value reported as "60 HB 10/1500/30" means that a Brinell Hardness of 60 was obtained using a 10mm diameter ball with a 1500 kilogram load applied for 30 seconds [4] .

2.10.2 Vickers hardness test

In Vickers hardness test indenter is consisting of a four-sided diamond pyramid with an acute angle (136°). Figure (2.17) shows the indentation area after Vickers load is released.

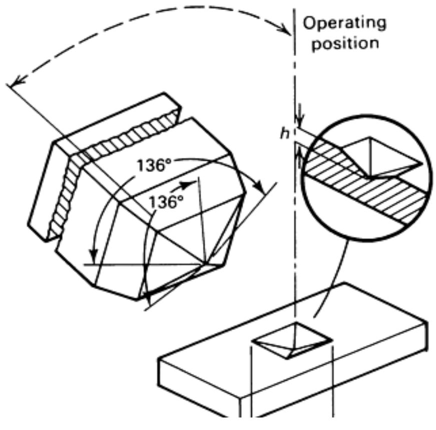


Figure 2-17 Diamond pyramid indenter and indentation shape [4]

$$\text{Vickers Hardness (HV)} = \frac{1.8544P}{d^2}$$ **Equation 2-8**

Where, P is the applied load (kg), d is an indentation diagonal (mm).

The procedure of Vickers testing is the same as the Brinell test, with the Vickers test showing the following advantages:

Due to the high hardness of the test indenter (Diamond) both soft and very hard materials can be tested.

The impressions are so small that also thin sheets and surface layers can be tested (surface heat treated parts). The result can be read more exact, so that inaccuracies are smaller using the Vickers than the Brinell test.

At materials with high differences in hardness in the structure (Micro-hardness test) however higher scattering is to be expected using the Vickers test since the hardness penetration is very small [7].

2.10.3 Rockwell hardness test

The Rockwell Hardness test also uses a machine to apply a specific load and then measure the depth of the resulting impression. The indenter may either be a steel ball of some specified diameter or a spherical diamond tipped cone of 120° angle and 0.2 mm tip radius. The most common Rockwell-process is the hardness test according to Rockwell C (HRC).

A minor load of 10 kg is first applied which causes a small initial penetration to seat the indenter and remove the effects of any surface irregularities. Then the dial is set to zero and the major load is applied. Upon removal of the major load the depth reading is taken while the minor load is still on figure (2.18). The hardness number may then be read directly from the scale.

For soft materials such as copper alloys, soft steel, and aluminium alloys a 1/16" diameter steel ball is used with a 100 kilogram load and the hardness is read on the "B" scale. In testing harder materials hard cast iron and many steel alloys a 120 degrees diamond cone is used with up to a 150 kilogram load and the hardness is read on the "C" scale. There are several Rockwell scales other than the "B" & "C" scales (common scales) table (2.1). Rockwell hardness value is read as the hardness number followed by "HR" (Hardness Rockwell) and the scale letter. For example 50 HRB indicates that the material has a hardness reading of 50 on the B scale.

The advantages of the Rockwell process against the processes according to Brinell and Vickers are the short time expenditure and the possibility of a fully automatic capture of the measuring value [7].

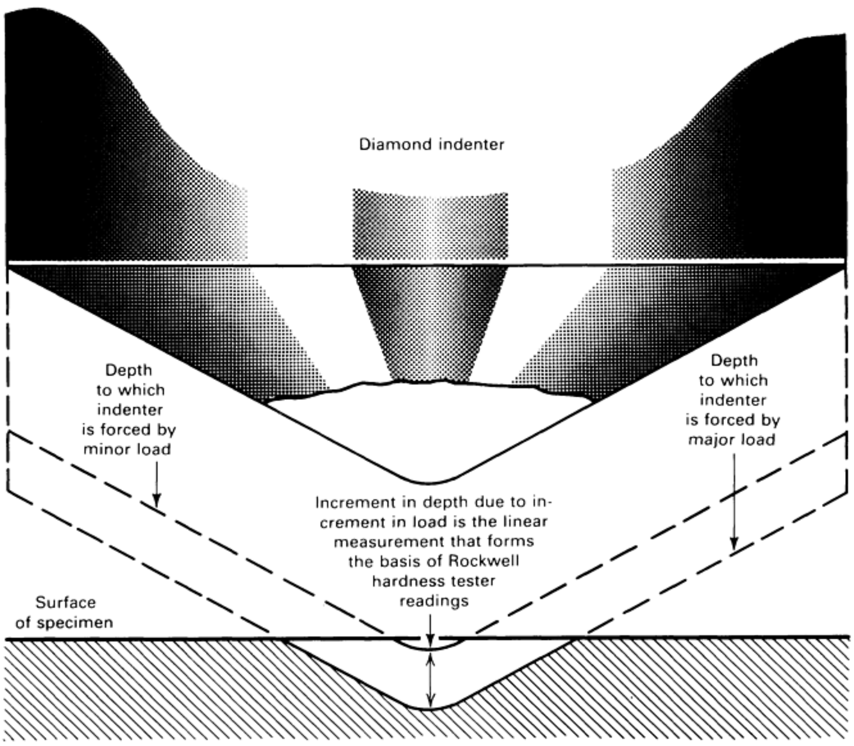


Figure 2-18 Principle of the Rockwell test [6]

Table 2-1 Common Rockwell hardness scales [6]

Scale	Indenter	Major load (kg)	Typical applications
A	Diamond cone	60	Cemented carbides, thin steel, and shallow case-hardened steel
B	Steel ball (1/16 in.)	100	Copper alloys, soft steels, aluminium alloys, malleable iron.
C	Diamond cone	150	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case-hardened steel, and other materials harder than 100 HRB.
D	Diamond cone	100	Thin steel and medium case-hardened steel and pearlitic malleable iron.
E	Steel ball (1/16 in.)	100	Cast iron, aluminium and magnesium alloys, bearing metals.

2.11 Hardness to strength conversion

The relationship between the hardness and tensile strength can not be linked to yield strength in the tensile test because the plastic deformation occurred is very small with respect to the hardness test, but could be linked to the ultimate tensile stress (UTS).

In all various hardness tests, the Brinell test may be ideal for this relationship, because the Brinell hardness values are in units of mass per unit area (kg/mm2) [7].

The following formulas can be used as guide to calculate the ultimate tensile strength of steels [6].

$$\sigma_{uts}(\text{MPa}) = 3.55\ \text{HB}\ (\text{HB} \leq 175)$$ **Equation 2-9**

$$\sigma_{uts}(\text{MPa}) = 3.55\ \text{HB}\ (\text{HB} > 175)$$ **Equation 2-10**

$$\sigma_{uts}(\text{psi}) = 515\ \text{HB}\ (\text{HB} \leq 175)$$ **Equation 2-11**

$$\sigma_{uts}(\text{psi}) = 490\ \text{HB}\ (\text{HB} > 175)$$ **Equation 2-12**

Where HB is the Brinell hardness of the material, as measured with a standard indenter and a 3000 kgf load, and UTS is ultimate tensile strength.

2.12 Hardness conversion from one scale to another

There is no clear relationship between the various hardness numbers, but there is an approximate relations based on the results of tests using the same materials of different ways. And it should be noted that these relations vary for different materials and for the mechanical and heat treatments to which they are exposed, which obligates the use of extreme caution.

From a practical standpoint it is important to be able to convert the results of one type of hardness test into those of a different test.

It is important to realize that hardness conversions are empirical relationships [7].

The ASTM, BS, and DIN standards are established a tables for conversion between Rockwell, Brinell , Vickers hardness, and tensile strength ,which is applicable to heat-treated carbon and alloy steel and to almost all alloy constructional steels and tool steels in as-forged, annealed, normalized, and quenched and tempered conditions, table (2.2, 2.3, 2.4).

Table 2-2 Hardness Conversion Chart according to B.S. 860/1939 [6]

Rockwell Scale		Diamond	Brinell			Tensile Stress Equivalents				Scleroscope
C	A	Pyramid Scale HV10 HV30	Dia. Imp. for 10mm Ball	Carbide Ball	Standard Ball	Tons/in2	1000lb/in2	kg/mm2	Mpa {N/mm2}	Hardness Number
67.7	85.6	900								96
67	85	880								95
66.3	84.7	860								93
65.5	84.2	840								92
64.8	83.8	820								90
64	83.4	800								88
63.3	83	780								87
62.5	82.6	760								86
61.7	82.2	740								84
61	81.8	725	2.44	630	-	-	-	-	-	82
60.5	81.5	710	2.45	627	-	-	-	-	-	-
60	81.2	698	2.5	601	-	132	295	208	2039	81
58.9	80.6	670	2.55	578	-	127	284	200	1961	78
57.1	79.6	630	2.6	555	-	122	273	192	1884	75
56.1	79	609	2.65	534	-	117	262	184	1807	73
54.4	78.2	572	2.7	514	-	112	250	176	1729	71
51.9	76.9	532	2.75	495	495	108	241	170	1668	68
50.7	76.3	517	2.8	477	477	105	235	165	1621	66
49.5	75.5	497	2.85	461	461	101	226	160	1559	64
47.5	74.2	470	2.9	444	444	98	219	155	1513	62
46	73.5	452	2.95	429	429	95	212	150	1467	60
44.8	73	437	3	415	415	92	206	145	1420	58
43.7	72.5	422	3.05	401	401	88	197	139	1359	56
42.4	71.5	408	3.1	388	388	85	190	134	1312	54
41.3	71	395	3.15	375	375	82	183	129	1266	52
39.9	70.3	381	3.2	363	363	80	179	126	1235	51
38.8	69.8	370	3.25	352	352	77	172	121	1189	49
37.7	69.2	359	3.3	341	341	75	168	118	1158	48
36.7	68.8	349	3.35	331	331	73	163	114	1127	46
35	68	337	3.4	321	321	71	159	111	1096	45
34	67.5	327	3.45	311	311	68	152	107	1050	43
33	66.8	318	3.5	302	302	66	147	104	1019	42
32	66.2	308	3.55	293	293	64	143	101	988	41
30.9	65.7	300	3.6	285	285	63	141	99	973	40
29.8	65.2	292	3.65	277	277	61	136	96	942	38
29	64.6	284	3.7	269	269	59	132	93	911	37
27.5	64	275	3.75	262	262	58	130	91	895	36
26.6	63.6	269	3.8	255	255	56	125	89	865	35
25.2	62.9	261	3.85	248	248	55	123	87	849	34
24.3	62.6	255	3.9	241	241	53	118	84	818	33
23	62	247	3.95	235	235	51	114	81	787	32
22	61.6	241	4	229	229	50	112	79	772	31
20.8	60.7	234	4.05	223	223	49	110	77	756	30
	-	228	4.1	217	217	48	107	76	741	-
Rockwell 'B' Scale										
98		222	4.15	212	212	46	103	73	710	29
97		218	4.2	207	207	45	101	71	695	28
96		212	4.3	197	197	43	97	68	664	27
93		196	4.4	187	187	41	92	65	632	25
91		188	4.5	179	179	39	88	62	602	-
88.5		178	4.6	170	170	36	81	57	556	24
86		171	4.7	163	163	35	78	55	540	-
84.2		163	4.8	156	156	34	76	54	525	23
82		156	4.9	149	149	32	72	51	494	-
80		150	5	143	143	3t	69	49	479	22
77		143	5.1	137	137	30	67	48	463	21
75		137	5.2	131	131	29.5	66	47	455	20.5
72.5		132	5.3	126	126	29	65	46	448	20
70		127	5.4	121	121	28	63	44	432	-
67		122	5.5	116	116	26	58	42	**401**	15

Comparison of hardness scales approx. & tensile stress equivalents approx. (maximum value) in imperial and metric units.

Table 2-3 ASTM Hardness Conversion Chart[6]

HRC150 kgf	HRA60 kgf	HRD100 kgf	HR15N 15kgf	HR30N 30kgf	HR45N45 kgf	Vickers Hardness	Knoop Hardness	Brinell Hardness 3000kgf 10mm	Tensile Strength
68	85.6	76.9	93.2	84.4	75.4	940	920	..	..
67	85	76.1	92.9	83.6	74.2	900	895	..	..
66	84.5	75.4	92.5	82.8	73.3	865	870	..	..
65	83.9	74.5	92.2	81.9	72	832	846	-739	
64	83.4	73.8	91.8	81.1	71	800	822	-722	
63	82.8	73	91.4	80.1	69.9	772	799	-705	
62	82.3	72.2	91.1	79.3	68.8	745	776	-688	
61	81.8	71.5	90.7	78.4	67.7	720	754	-670	
60	81.2	70.7	90.2	77.5	66.6	697	732	-654	
59	80.7	69.9	89.8	76.6	65.5	674	710	-634	351
58	80.1	69.2	89.3	75.7	64.3	653	690	615	338
57	79.6	68.5	88.9	74.8	63.2	633	670	595	325
56	79	67.7	88.3	73.9	62	613	650	577	313
55	78.5	66.9	87.9	73	60.9	595	630	560	301
54	78	66.1	87.4	72	59.8	577	612	543	292
53	77.4	65.4	86.9	71.2	58.6	560	594	525	283
52	76.8	64.6	84.4	70.2	57.4	544	576	512	273
51	76.3	63.8	85.9	4	56.1	528	558	496	264
50	75.9	63.1	85.5	68.5	55	513	542	481	255
49	75.2	62.1	85	67.6	53.8	498	526	469	246
48	74.7	61.4	84.6	66.7	52.5	484	510	455	237
47	74.1	60.8	83.9	65.8	51.4	471	495	443	229
46	73.6	60	83.5	64.8	50.3	458	480	432	221
45	73.1	59.2	83	64	49	446	466	421	215
44	72.5	58.5	82.5	63.1	47.8	434	452	409	208
43	72	57.7	82	62.2	46.7	423	438	400	201
42	71.5	56.9	81.5	61.3	45.5	412	426	390	195
41	70.9	56.2	80.9	60.4	44.3	402	414	381	188
40	70.4	55.4	80.4	59.5	43.1	392	402	371	182
39	69.9	54.6	79.9	58.6	41.9	382	391	362	177
38	69.4	53.8	79.4	57.7	40.8	372	380	353	171
37	58.9	53.1	78.8	56.8	39.6	363	370	344	166
36	68.4	52.3	78.3	55.9	38.4	354	360	336	161
35	67.9	51.5	77.7	55	37.2	345	351	327	156
34	67.4	50.8	77.2	54.2	36.1	336	342	319	152
33	66.8	50	76.6	53.3	34.9	327	334	311	149
32	66.3	49.2	76.1	52.1	33.7	318	326	301	146
31	65.8	48.4	75.6	51.3	32.5	310	318	294	141
30	65.3	47.7	75	50.4	31.3	302	311	286	138
29	64.8	47	74.5	49.5	30.1	294	304	279	135
28	64.3	46.1	73.9	48.6	28.9	286	297	271	131
27	63.8	45.2	73.3	47.7	27.8	279	290	264	128
26	63.3	44.6	72.8	46.8	26.7	272	284	258	125
25	62.8	43.8	72.2	45.9	25.5	266	278	253	123
24	62.4	43.1	71.6	45	24.3	260	272	247	119
23	62	42.1	71	44	23.1	254	266	243	117
22	61.5	41.6	70.5	43.2	22	248	261	237	115
21	61	40.9	69.9	42.3	20.7	243	256	231	112
20	60.5	40.1	69.4	41.5	19.6	238	251	226	110

Approximate hardness numbers for Non-Austenitic Steels .according to ASTM E-140.
The conversion values contained herein should be considered approximate only may be inaccurate for specific applications.

Table 2-4 Hardness conversion chart according to DIN 50 150 [9]

Vickers hardness ($F \geqq 98N$)	Ball indentation diameter[1])	Brinell hardness[2])	Rockwell hardness		Tensile strength
HV	mm	HB	HRB	HRC	N/mm^2
63	7.32	60			200
65	7.22	62			210
69	7.04	66			220
70	6.99	67			225
72	6.95	68			230
75	6.82	71			240
79	6.67	75			250
80	6.63	**76**			**255**
82	6.56	78			260
85	6.45	81	**41**		**270**
88	6.35	84	45		280
90	6.28	86	**48**		**285**
91	6.25	87	49		290
94	6.19	89	51		300
95	6.16	90	**52**		**305**
97	6.10	92	54		310
100	6.01	**95**	56		**320**
103	5.93	98	58		330
105	5.87	100	59		**335**
107	5.83	102	60		340
110	5.75	**105**	62		**350**
113	5.70	107	63.5		360
115	5.66	**109**	64.5		**370**
119	5.57	113	66		380
120	5.54	**114**	67		**385**
122	5.50	116	67.5		390
125	5.44	**119**	69		**400**
128	5.38	122	70		410
130	5.33	**124**	71		**415**
132	5.32	125	72		420
135	5.26	**128**	73		**430**
138	5.20	131	74		440
140	5.17	**133**	**75**		**450**
143	5.11	136	76.5		460
145	5.08	**138**	77		**465**
147	5.05	140	77.5		470
150	5.00	**143**	78.5		**480**
153	4.96	145	79.5		490
155	4.93	**147**	80		**495**
157	4.90	149	81		500
160	4.86	**152**	81.5		**510**
163	4.81	155	82.5		520
165	4.78	157	83		**530**
168	4.74	160	84.5		540
170	4.71	**162**	**85**		**545**
172	4.70	163	85.5		550
175	4.66	**166**	86		**560**
178	4.62	169	86.5		570
180	4.59	**171**	87		**575**
181	4.58	172			580
184	4.54	175	88		590
185	4.53	**176**			**595**
187	4.51	178	89		600
190	4.47	**181**	**89.5**		**610**
193	4.44	184	90		620
195	4.43	**185**			**625**
197	4.40	187	91		630
200	4.37	**190**	**91.5**		**640**
203	4.34	193	92		650
205	4.32	**195**	**92.5**		**660**
208	4.29	198	93		670
210	4.27	**199**	**93.5**		**675**
212	4.25	201			680
215	4.22	**204**	**94**		**690**
219	4.19	208			700
220	4.18	**209**	**95**		**705**
222	4.16	211	95.5		710
225	4.13	**214**	**96**		**720**
228	4.11	216			730
230	4.08	**219**	96.5		**740**
233	4.07	221	97		750
235	4.05	**223**			**755**
237	4.03	225	97.5		760
240	4.01	**228**	98		**770**
243	3.98	231		21	780
245	3.97	**233**			**785**
247	3.95	235	99		790
250	3.93	**238**	**99.5**	22	**800**
253	3.91	240			810
255	3.89	**242**		23	**820**
258	3.87	245			830
260	3.85	**247**		**24**	**835**
262	3.84	249			840
265	3.82	**252**			**850**
268	3.80	255		25	860
270	3.78	**257**			**865**
272	3.77	258		26	870
275	3.76	**261**			**880**
278	3.74	264			890
280	3.72	**266**		27	**900**
283	3.70	269			910
285	3.69	**271**			**915**
287	3.68	273		28	920
290	3.66	**276**			**930**
293	3.64	278		29	940
295	3.63	**280**			**950**
299	3.61	284			960
300	3.60	**285**			**965**
302	3.59	287		30	970
305	3.57	290			980
308	3.55	293			990
310	3.54	**295**		**31**	**995**
311	3.53	296			1000
314	3.52	299			1010
317	3.50	301		32	1020
320	3.49	**304**			**1030**
323	3.47	307			1040
327	3.45	311		33	1050
330	3.44	**314**			**1060**
333	3.43	316			1070
336	3.41	319		34	1080
339	3.40	322			1090
340	3.39	**323**			**1095**
342	3.38	325			1100
345	3.36	328		35	1110
349	3.35	332			1120
350	3.34	**333**			**1125**
352	3.33	334			1130
355	3.32	337		36	1140
358	3.31	340			1150
360	3.30	342			**1155**
361	3.29	343			1160
364	3.28	346		37	1170
367	3.26	349			1180
370	3.25	352			**1190**
373	3.24	354		38	1200

[1]) steel ball with 10 mm diameter; [2]) calculated from: HB = 0.95 HV

Vickers hardness ($F \geqq 98N$)	Ball indentation diameter[1]	Brinell hardness[2]	Rockwell hardness		Tensile strength
HV	mm	**HB**	**HRB**	**HRC**	**N/mm²**
376	3.23	357			1210
380	3.21	361			**1220**
382	3.20	363		39	1230
385	3.19	366			1240
388	3.18	369			1250
390	3.17	371			**1255**
392		372		40	1260
394	3.16	374			1270
397	3.14	377			1280
400	3.13	380			**1290**
403	3.12	383		41	1300
407	3.10	387			1310
410	3.09	390			**1320**
413	3.08	393		42	1330
417	3.07	396			1340
420	3.06	399			**1350**
423	3.05	402		43	1360
426	3.04	405			1370
429		408			1380
430	3.02	409			**1385**
431		410			1390
434	3.01	413		44	1400
437	3.00	415			1410
440	2.99	**418**			**1420**
443	2.98	421			1430
446	2.97	424		45	1440
449	2.96	427			1450
450		**428**			**1455**
452	2.95	429			1460
455	2.94	432			1470
458	2.93	435		46	1480
460		**437**			**1485**
461	2.92	438			1490
464	2.91	441			1500
467	2.90	444			1510
470	2.89	**447**			**1520**
473		449		47	1530
476	2.88	452			1540
479	2.87	455			1550
480		**(456)**			**1555**
481	2.86	(457)			1560
484	2.85	(460)		48	1570
486		(462)			1580
489	2.84	(465)			1590
490	2.83	**(466)**			**1595**
491		(467)			1600
494	2.82	(470)			1610
497		(472)		49	1620
500		**(475)**			**1630**
503	2.80	(478)			1640
506	2.79	(481)			1650
509		(483)			1660
510	2.78	**(485)**			**1665**
511		(486)			1670
514	2.77	(488)		50	1680
517	2.76	(491)			1690
520	**2.75**	**(494)**			**1700**
522		(496)			1710
525	2.74	(499)			1720
527		(501)		51	1730
530	2.73	**(504)**			**1740**
533	2.72	(506)			1750
536	2.71	(509)			1760
539		(512)			1770
540	2.70	**(513)**			**1775**
541		(514)			1780
544	2.69	(517)		52	1790
547		(520)			1800
550	2.68	**(523)**			**1810**
553	2.67	(525)			1820
556		(528)			1830
559	2.66	(531)			1840
560		**(532)**		**53**	**1845**
561	2.65	(533)			1850
564		(536)			1860
567	2.64	(539)			1870
570		**(542)**			**1880**
572	2.63	(543)			1890
575	2.62	(546)			1900
578		(549)		54	1910
580	2.61	**(551)**			**1920**
583	2.60	(554)			1930
586		(557)			1940
589	2.59	(560)			1950
590		**(561)**			**1955**
591		(562)			1960
594	2.58	(564)			1970
596		(567)			1980
599	2.57	(569)			1990
600		**(570)**			**1995**
602	2.56	(572)			2000
605		(575)			2010
607	2.55	(577)			2020
610		**(580)**			**2030**
613	2.54	(582)			2040
615		(584)		56	2050
618	2.53	(587)			2060
620		**(589)**			**2070**
623	2.52	(592)			2080
626		(595			2090
629	2.51	(598)			2100
630		**(599)**			**2105**
631		(600)			2110
634	2.50	(602)			2120
636		(604)			2130
639	2.49	(607)		57	2140
640		**(608)**			**2145**
641		(609)			2150
644	2.48	(612)			2160
647	2.47	(615)			2170
650		**(618)**			**2180**
653		(620)			2190
655	2.46	(622)		58	2200
675				59	
698				60	
720				**61**	
745				62	
773				63	
800				**64**	
829				65	
864				66	
900				**67**	
940				**68**	

[1]) steel ball with 10 mm diameter; [2]) calculated from: HB = 0.95 HV

Values in bold face correspond exactly to DIN values. The other values are interpolated. Values in parenthesis are values outside the defined range of standardized hardness testing procedures. Also, Brinell hardness numbers in parenthesis apply only when testing with carbide ball.

2.13 Machinability

The term machinability refers to the ease with which a metal can be machined to an acceptable surface finish. Materials with good machinability require little power to cut, can be cut quickly, easily obtain a good finish, and do not wear the tooling much; such materials are said to be free machining. The factors that typically improve a material's performance often degrade its machinability. Therefore, to manufacture components economically, engineers are challenged to find ways to improve machinability without harming performance.

Machinability can be difficult to predict because machining has so many variables. Two sets of factors are the condition of work materials and the physical properties of work materials.

The condition of the work material includes eight factors: microstructure, grain size, heat treatment, chemical composition, fabrication, hardness, yield strength, and tensile strength.

Physical properties are those of the individual material groups, such as the modulus of elasticity, thermal conductivity, thermal expansion, and work hardening.

Other important factors are operating conditions, cutting tool material and geometry, and the machining process parameters [5].

2.13.1 Methods of measuring machinability

There are many factors affecting machinability, but no widely accepted way to quantify it. Instead, machinability is often assessed on a case-by-case basis, and tests are tailored to the needs of a specific manufacturing process. Common metrics for comparison include tool life, surface finish, cutting temperature, and tool forces and power consumption [3].

2.13.1.1 Tool life method

Machinability can be based on the measure of how long a tool lasts. This can be useful when comparing materials that have similar properties and power consumptions, but one is more abrasive and thus decreases the tool life. The major downfall with this approach is that tool life is dependent on more than just the material is it machining; other factors include cutting tool material, cutting tool geometry, machine condition, cutting tool clamping, cutting speed, feed, and depth of cut. Also, the machinability for one tool type cannot be compared to another tool type (i.e. HSS tool to a carbide tool).

2.13.1.2 Tool forces and power consumption method

The forces required for a tool to cut through a material are directly related to the power consumed. Therefore, tool forces are often given in units of specific energy. This leads to a rating method where higher specific energies equal lower machinability. The advantage of this method is that outside factors have little effect on the rating.

2.13.1.3 Machinability Surface finish method

The surface finish is sometimes used to measure the machinability of a material. Soft, ductile materials tend to form a built up edge. Stainless steel and other materials with a high strain hardening ability also want to form a built up edge. Aluminium alloys, cold worked steels, and free machining steels, as well as materials with a high shear zone don't tend to form built up edges, so these materials would rank as more machinable

The advantage of this method is that it is easily measured with the appropriate equipment. The disadvantage of this criterion is that it is often irrelevant. For instance when making a rough cut, the surface finish is of no importance. Also, finish cuts often require a certain accuracy that naturally achieves a good surface finish. This rating method also doesn't always agree with other methods. For instance titanium alloys would rate well by the surface finish method, low by the tool life method, and intermediate by the power consumption method.

2.13.1.4 Machinability rating

The machinability rating of a material attempts to quantify the machinability of various materials. It is expressed as a percentage or a normalized value. The American Iron and Steel Institute (AISI) determined machinability ratings for a wide variety of materials by running turning tests at 180 surface feet per minute. It then arbitrarily assigned 160 Brinell B1112 steel a machinability rating of 100%. The machinability rating is determined by measuring the weighted averages of the normal cutting speed, surface finish, and tool life for each material.

Note that a material with a machinability rating less than 100% would be more difficult to machine than B1112 and material with a value more than 100% easier [6].

Chapter 3

3 HEAT TREATMENT AND WELDABILITY OF STEELS

3.1 Introduction of heat treatment

To change the properties of a metal, it is essential that heat treatment produce certain residual changes in its structure resulting from phase transformations. If a microstructure of metal is unstable, heating can increase the mobility of atoms and the metal will approach the equilibrium state in which heat treatment will be possible without phase transformation. The heat treatment of steel is a combination of heating to a proper temperature and keep it for a certain time (holding time) then cooling to room temperature by controlling a cooling rate depending on properties required. The rate of heating up of steel to some temperature is less important factor in heat-treating process than other factors such as temperature, holding time, and cooling rate , but if the component is highly stressed the heating up cycle must be as slow as possible to avoid the distortion and crack. The heating up temperature of steel and the cooling rate depends on the chemical composition of this steel and the heat treatment and mechanical properties required, but the holding time depends on the component cross section. The heat treatment procedure of steel and the properties required strongly affected by the type and percentage of alloying elements in the steel , such as Carbon, Chromium, Nickel, Vanadium, tungsten , and …etc. The heat treatments process may be entail transformations of the structural constituents without any change in the average chemical composition of the material, the figure (3.1) below comprises the major heat treatment processes. The temperature ranges of major heat treatment processes applicable to unalloyed steels are shown in the figure (3.2) iron-iron carbide diagram. As for alloyed steels the transformation temperatures change with the contents of alloying elements, the temperature ranges for individual heat treatment processes also change [8].

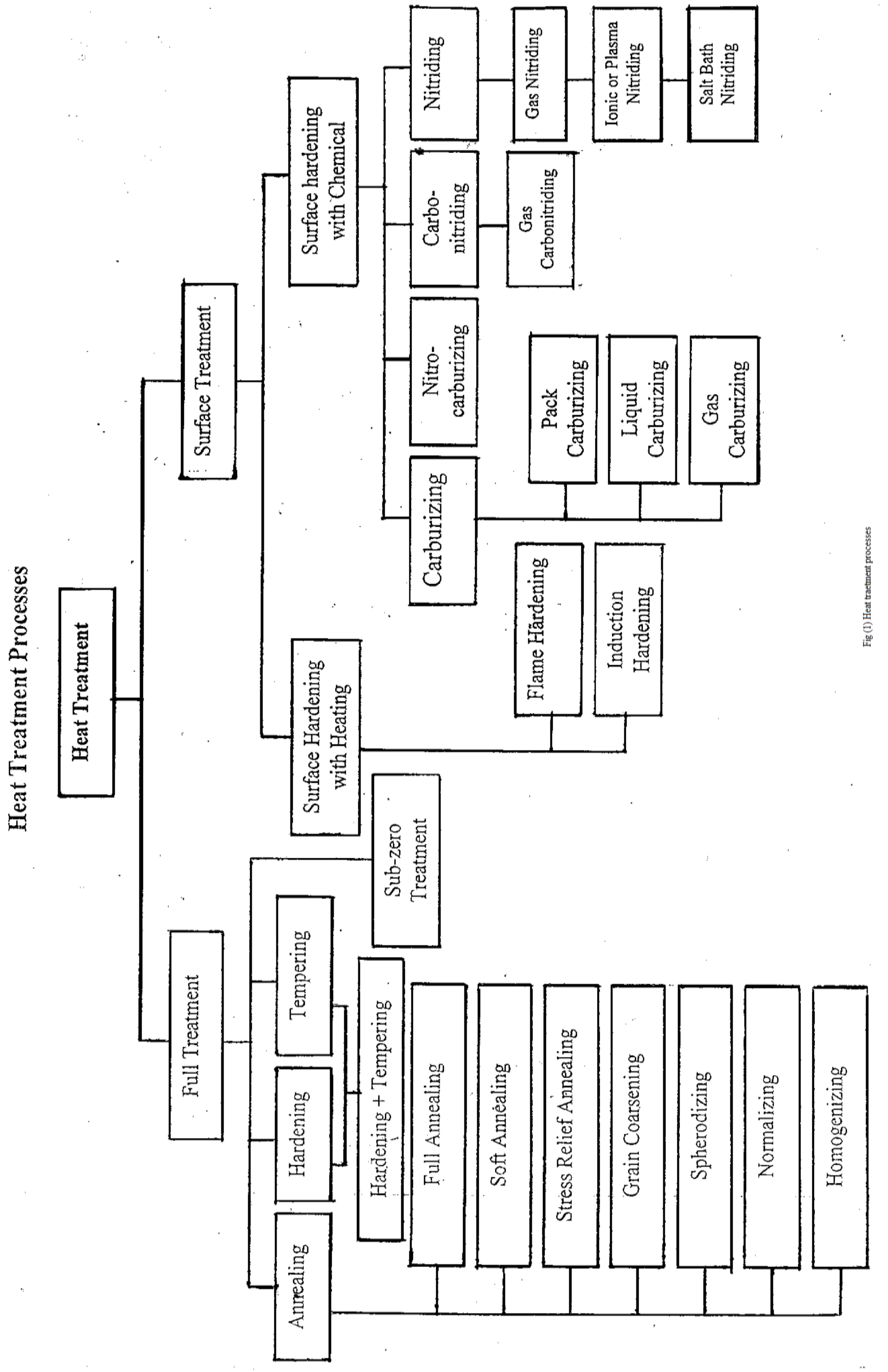


Figure 3-1 Heat Treatment processes

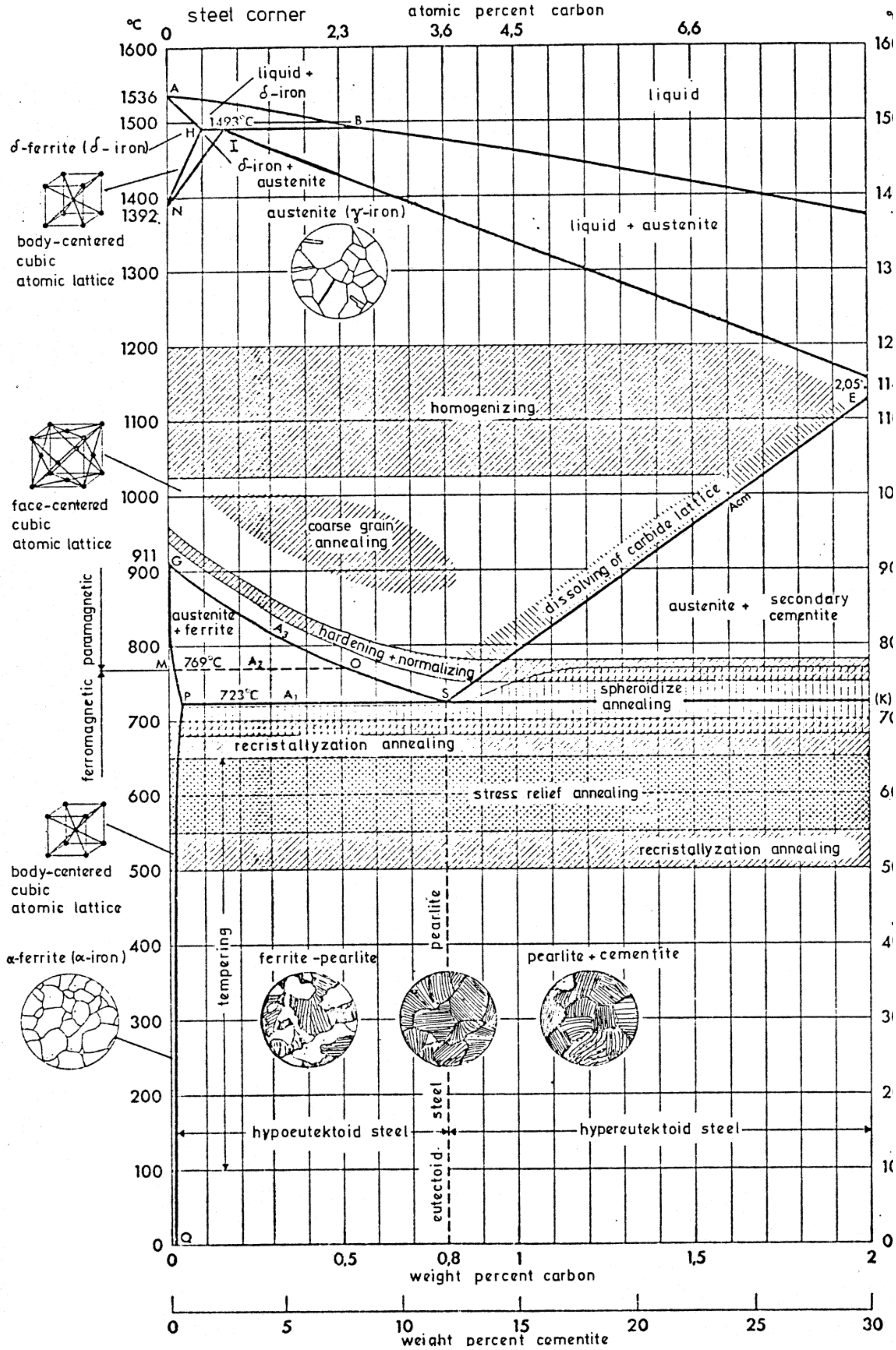


Figure 3-2 Areas of heat treatment (Fe-C diagram partly) [9]

3.2 Heat treatment processes

3.2.1 Full heat treatment

3.2.1.1 Annealing

Heating the steel to a temperature above the phase transformation and then cooled slowly to obtain a structurally stable state, the purpose of the annealing is to refine grain size and improve machinability.

In full annealing, hypo eutectoid and eutectoid steels are heated about 30 to 50 ^{0}C above their AC_3 (upper critical) temperature, held the necessary time and then cooled slowly to room temperature, in hypereutectoid steels heated above AC_1 (lower critical) temperature, but this treatment will result in poor machinability, so for hypereutectoid steels annealing should never be a final heat treatment [9].

3.2.1.2 Spheroidizing annealing:

As mentioned earlier hypereutectoid steels will be brittle after annealing, because of cementite net work formed surround pearlite grains this will give a poor machinability. A heat treating process which will improve the Machinability is known as Spheroidizing annealing. This process will produce a spheroidal or globular form of carbides in ferritic matrix.

One of the following methods may be used:

- Prolonged holding at temperature just below the lower critical temperature (AC_1).
- Heating and cooling alternately between temperatures that are just above and just below the lower critical temperature.
- Heating to a temperature above the lower critical temperature and then either cooling very slowly in the furnace or holding at a temperature just below the lower critical temperature.

The sheroidized structure is desirable when minimum hardness, maximum ductility or (in high carbon steels) maximum machinability is important [10].

3.2.1.3 Process annealing

Process annealing is used for hypo-eutectoid steels (wires & sheets) by heating the steels to a temperature below the lower critical temperature, usually about 550 to 650 ^{0}C held for necessary time and then cooled at desired rate

This treatment is applied after cold working and softens the steel, by recrystallization, for further working [9].

3.2.1.4 Stress relief annealing

Stress-relief heat treatment is understood as annealing below AC1 with subsequent slow cooling so that internal stresses will be reduced without an essential influence on the other properties. However, it has to be noticed that a complete stress-free state of the material is practically not achievable. Internal stresses can be generated due to different heat dilatation or due to the shrinkage behaviour of the material e.g. during welding, soldering, solidification or quenching. Due to internal stresses the material can be distorted or even be cracked.

Additionally, internal stresses within the work piece can be relieved by plastic deformation. In doing so, the yield strength of the material should be lowered below the sum of the stresses.

With unalloyed steels the most favourable annealing temperatures is between 450 and 600°C at a soaking time of 1 to 2 h [10].

3.2.1.5 Normalizing

Normalizing means the heating of steels to temperatures of 30 to 50°C above the (AC_3) temperature with hypo eutectoid steels and 30 to 50°C above (AC_1) with hypereutectoid steels. Depending on the dimensions the respective work piece will be exposed to the heating temperature only as long as it is necessary to heat it up completely. After that it will be cooled at resting air.

Due to the fact that the steel is twice subject to a ferrite – austenite (α/γ) transformation, the material will be transformed into a uniform, fine grained structure. Therefore, the objective of normalizing is to change an irregular and coarse grain structure into a uniform one with fine lamellar ferrite-pearlite structure. Thus, all structural changes by means of hardening, tempering, superheating, welding, or cold- and hot forming will be removed by normalizing as far as no durable defects such as curtaining or hardening cracks have occurred.

A fast passage of the ferrite - austenite region (α/γ) supports the formation of a fine structure.

Normalizing is to be recommended in the following cases:

- In case of a non-uniform structure, e.g. after superheating or in case of ferrite- pearlite bands.
- In case of coarse grain.
- In case of a solidification structure, e.g. at a weld joint or steel cast.
- In case of steels embrittled due to aging.
- In case of all building steels having an insufficient toughness or to less of a yield. [11]

3.2.1.6 Recrystallization

During cold deformation all parts of the structure that are plastic formable can be lengthen in the direction of the deformation (strengthening) with a simultaneous build up of internal stresses. This hardened state is characterized by an increase in strength with a simultaneous reduction of the formability. Due to this reason cold deformation cannot be carried out endlessly, but after a certain reduction ratio recrystallization is necessary in order to restore the original material properties. Every metal and every alloy has a specified recrystallization temperature. Above this temperature the crystal lattice will be rebuild due to the thermal energy introduced. The recrystallization temperature of pure metals can be approximated by:

TR 0.42 *TS TR: recrystallization temperature TS: melting temperature of the metal in K.

The recrystallization temperature is essentially dependent on the deformation grade and the alloying components. With unalloyed steels the recrystallization temperature is between 450 and 600°C, with alloyed steels depending on the alloy content between 600 and 800°C.

By means of recrystallization (primary recrystallization) the grains are completely formed again. Above the recrystallization temperature the small grains formed by the primary recrystallization combine to form a few, large grains. This process is called secondary recrystallization. The grain size obtained by recrystallization is among others dependent on the deformation grade: The higher the deformation grade, the finer the grain structure becomes.

At a critical deformation grad between 5 and 20 % there a very few crystal nuclei, thus leading to an undesired grain coarsening [11].

3.2.1.7 Hardening

Hardening is a heat treatment with following cooling at a speed that leads to increasing the hardness by the formation of martensite.

In order to obtain maximum hardness in plain carbon steel, it must be quenched from austenizing temperature (above AC_3 for hypo-eutectoid steels and above AC_1 hypereutectoid steels); at such rate that a martensitic structure is produced throughout the entire part figure (3.3). To obtain a fully martensitic structure the steel must be quenched at a rate equal to or greater than the critical cooling rate to achieve maximum hardness.

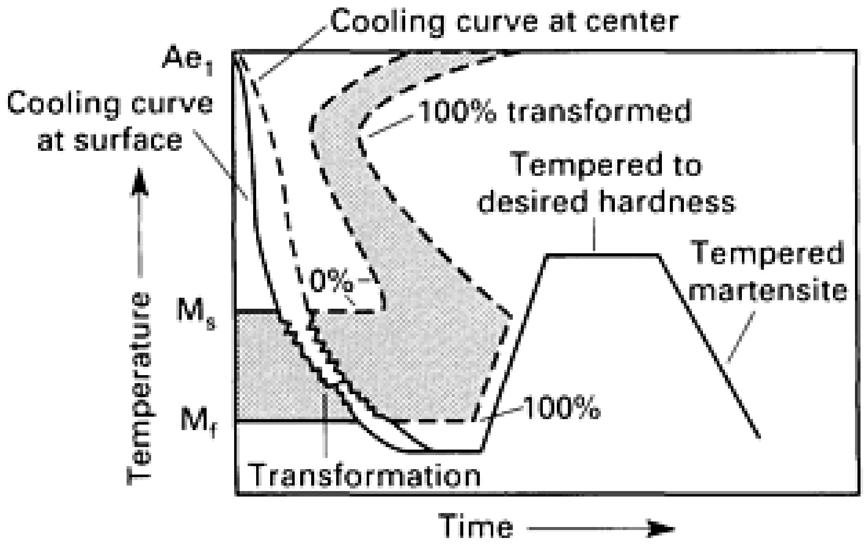


Figure 3-3 Temperature cycle during hardening [9]

Since the critical cooling rate for some plain carbon steels is so fast (such as 0.80% C plain carbon steel), only thin steel shapes can be made fully martensitic. If thick sections are rapidly cooled, the surface will call more rapidly than the centre. Thus, using conventional quenchants, fully martensitic structures cannot be obtained in plain carbon steels with thick sections no matter how fast the cooling so, alloying elements such as Nickel, Chromium, and Molybdenum are added to plain carbon steels thus increasing the time during quenching before the critical rate is reached.

The quenching media most commonly used for steels are water, Water brine, oils, and salt baths. In general brine (water pulse various percentage of sodium chloride or calcium chloride) provides a faster cooling rate than water. Oil, on the other hand, cools at a slower rate than water; in general, agitation of quench media increases the cooling rate [12].

- **Quench cracks:** The volume changes, which occur when austenite is cooled, are: (a) expansion when gamma iron transforms to ferrite; (b) contraction when cementite is precipitated; (c) normal thermal contraction. When steel is quenched these volume changes occur very rapidly and unevenly throughout the specimen. The outside cools most quickly, and is mainly martensitic, in which contraction (d) has not occurred. The centre may be pearlitic-ferritic and contraction (e) started. Stresses are set up which may cause the metal either to distort or to crack if the ductility is insufficient for plastic flow to occur. Such cracks may occur sometime after the quenching or in the early stages of tempering.

Quench cracks are liable to occur:

a) Due to presence of non-metallic inclusions, cementite masses …etc.

b) When austenite is coarse grained due to high quenching temperature.

c) Owing to uneven quenching.

d) In pieces of irregular section and when sharp re-entrant angles are present in the design.

The relation of design to heat-treatment is very important. Articles of irregular section need special care. When steel has been chosen which needs a water-quench, then the designer must use generous fillets in the corners and a uniform section should be aimed at. This can sometimes be obtained by boring out metal from bulky parts without materially affecting the design. A hole drilled from the side to meet a central hole may cause cracking and it should be drilled right through and temporarily stopped up with asbestos wool during heat-treatment. A crack would also form at the junction of the solid gear with the shaft. There is a serious danger of cracks at the roots of the teeth, owing to the great change in size of section. This design could be improved by machining the metal away under the rim to make a cross-section of uniform mass.

- **Work piece design:** In order to avoid damage due to cracking or fracture in the heat treatment a number of rules must be followed already in the stage of tool or component design. Avoid sharp transitions between different cross sections by way of rounding of corners. The final shape or dimension should be produced only after the hardening operation such as grinding. Whenever possible, the component should be of symmetrical shape. If possible, additional holes or recesses should be provided to obtain a more uniform mass distribution. All corners, edges, recesses, fillets, shoulders should be provided with maximum possible radii. All notched should be avoided. If necessary, design tools in two parts to avoid areas of very high crack sensitivity. Examples are given in figure (3.4) [13].

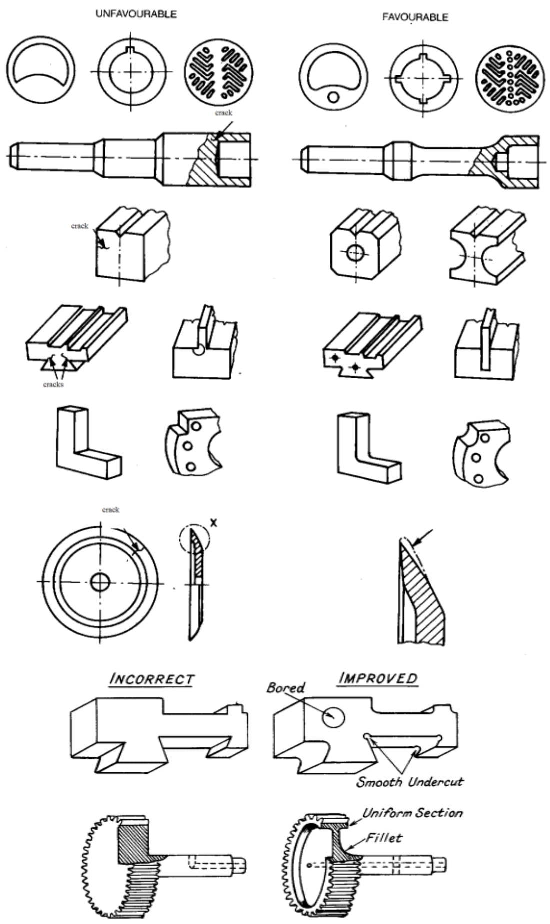


Figure 3-4 Favourable and unfavourable parts design for heat treatment [9]

- **Hardenability:** is understood as the capability of steel to adopt an increased cross-sectional by means of modification to the martensitic state. The term hardenability comprises both, the extent of the hardness (increase of hardness) and the distribution of the hardness (deep hardenability). If a work piece is completely modified into the martensite structure all over its total cross-section, it is called core hardening.

The term hardenability comprises hardness increase and hardness penetration. The term hardness increase defines the maximum achievable hardness of a material under optimum conditions. It depends on the percentage of carbon dissolved in the austenite.

Figure (3.5) shows the maximum hardness achievable according to carbon content in the steel**.**

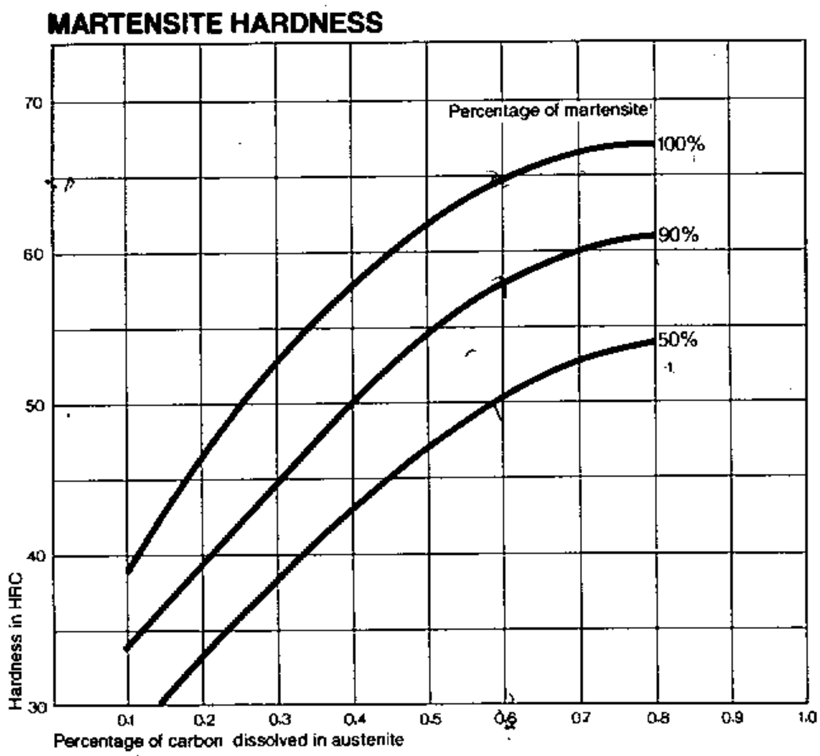


Figure 3-5 Maximum hardness achievable depending on carbon content [9]

Hardness penetration means hardening effect over the whole cross section of a work piece which is determined by the critical cooling rate for martensite formation and thus, side from carbon content, by the content of alloying element and by the grain size.

The term hardness penetration stands for the maximum achievable depth of hardening produced by grinding under optimum conditions figure (3.6) [13].

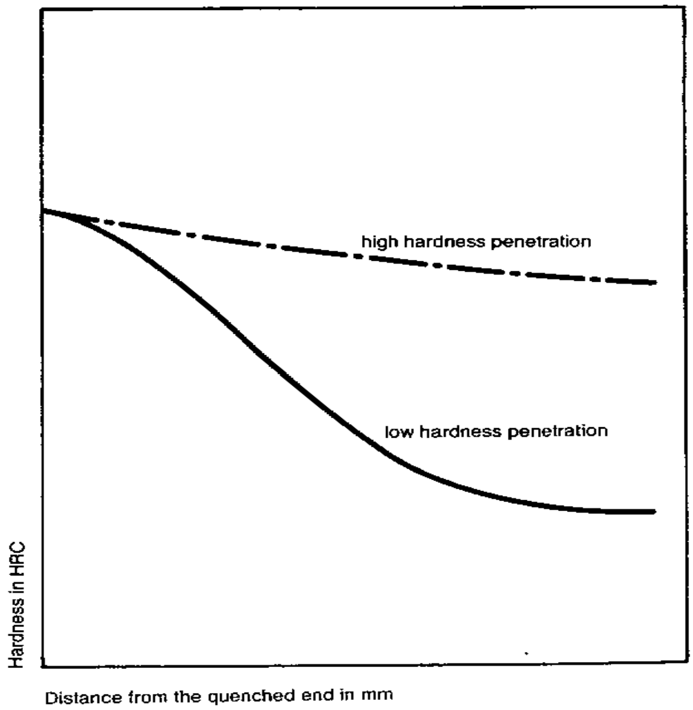


Figure 3-6 Hardness penetration after quenching

The term hardening depth is defines as the vertical distance from the surface of hardened work piece to that point where the hardness is still within a specified limit. A common procedure for testing the hardenability is the Jominy test. It consists of quenching an austenitized specimen (Φ 25 mm, 100 mm length) in a suitable fixture from the lower end face with a jet of water under constant test conditions. The cooling rate and consequently also the hardness which is measured along the ground surface area of the specimen after quenching decreases with increasing distance from the quenched end. The course of hardening curve is characteristic for the hardenability. With constant carbon content, hardness increase is uniform. Hardness penetration, on the other hand, depends on the chemical composition. The chemical composition and carbon content steel have strong effect on hardenability of steel figures (3.7 & 3.8) [12].

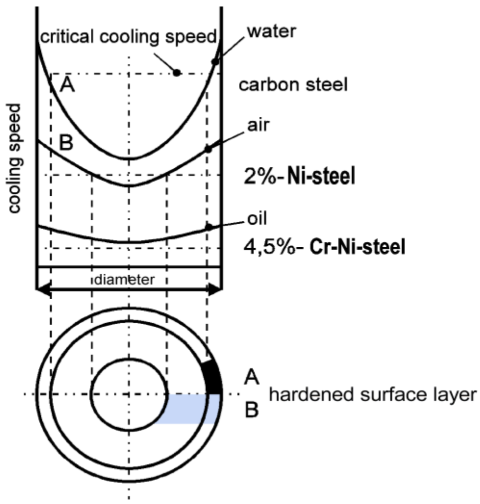


Figure 3-7 Influence of the alloy on the core hardening capability of steels [12]

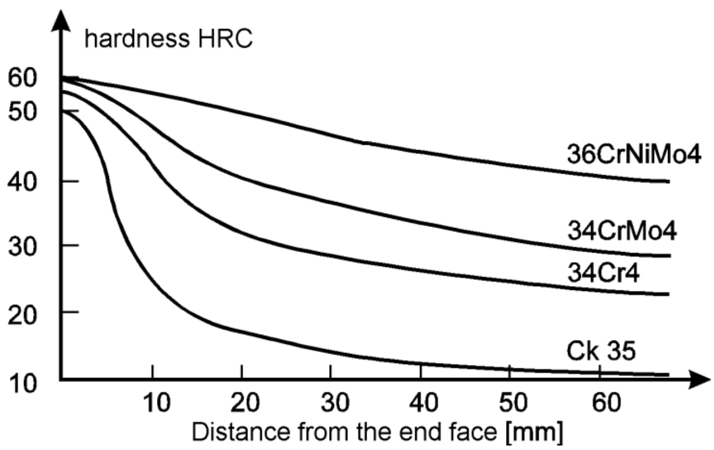


Figure 3-8 Jominy curves of steels of the same C-content with different contents of alloying elements [9]

3.2.1.8 Tempering

Tempering is heating of a hardened work piece to a temperature between room temperature and AC_1, keeping this temperature and afterwards cooling. By means of tempering the strength or proof stress will be decreased and elongation or necking will be increased. The tempering temperature is to be selected such, that a comparably high amount of hardness together with an acceptable toughness for a predetermined application will be obtained.

During the tempering process of hardened steel different processes take place depending on the tempering stage:

1st tempering stage up to approx. 150°C

- The C-atoms diffuse on interstitial places.
- The tetragonal distortion decreases depending on temperature and time.
- Precipitation of submicroscopic iron-carbide crystals.

2nd tempering stage approx. 150°C up to approx. 290°C

- Change of position of C-atoms in the lattice and transformation of Tetra-hexagonal martensite into cubic martensite.
- Precipitation of finest iron carbides.
- Shearing of residual austenite into cubic martensite.

3rd tempering stage approx. 290°C up to approx. 400°C

- Precipitation of all of the carbon as carbides.
- The cubic martensite is more and more transformed into the cubic ferrite (free of carbon).

4th tempering stage approx. 400°C up to approx. 723°C

- Ferrite with embedded carbides.
- Coagulation of the carbides.

The individual tempering stages cannot be separated from each other, they merge into one another. The toughness of Cr, Mn, and Cr-Ni steels will be decreased, if it is tempered at certain temperature ranges. Due to the range of the loss of toughness of T = 300°C to 350°C this fact is called “300°C-embrittlement”. Some steels, in particular Mn, Cr, Cr-Mn and Cr-Ni-steels show a decreased toughness after slow cooling (e.g. in the furnace) during tempering. At a fast cooling (air, water) there will be no embitterment. Since this embitterment takes place at a tempering temperature of approx. 500°C it is called “500°C embitterment”. Steels that are among the above mentioned alloy types should not be tempered in the temperature range of 300°C to 500°C, but either below or above these temperatures. Tool steels that contain a larger amount of carbide forming elements (chromium, vanadium, molybdenum, tungsten) are tempered several times, thus leading to a “secondary hardness maximum” with high alloyed tool steels and high-speed steels figure (3.9) [15].

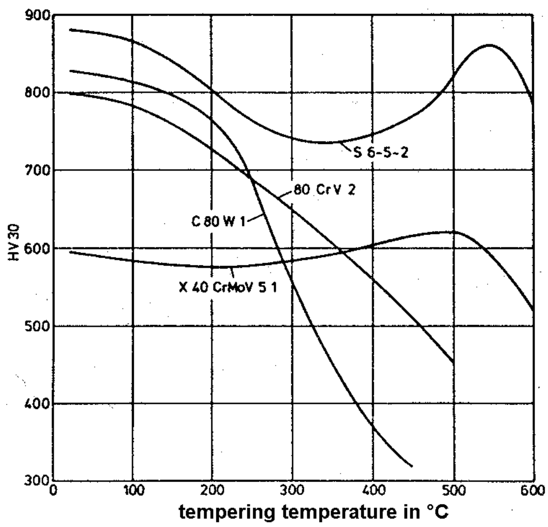


Figure 3-9 Tempering treatment of cold, hot working and high speed steels [8]

3.2.1.9 Austempering

Austempering is an isothermal heat treatment process, which produces a bainite structure in plain carbon steels the process provides an alternative procedure to quenching and tempering for optimizing strength and toughness of some steels for certain hardness levels. For austempering, the steel is austenitized, quenched into a hot salt bath at a temperature just below the Ms (martensite start) temperature, held isothermally, and then cooled to room temperature in air.

Austempering is usually substituted for conventional quenching and tempering to obtain improved ductility and impact strength for particular hardness and to decrease cracking and distortion quenching. Figure (3.10) Comparison of time-temperature transformation cycles for conventional quenching and tempering and for austempering (A=Austenite F=Ferrite & C=Cementite) [12].

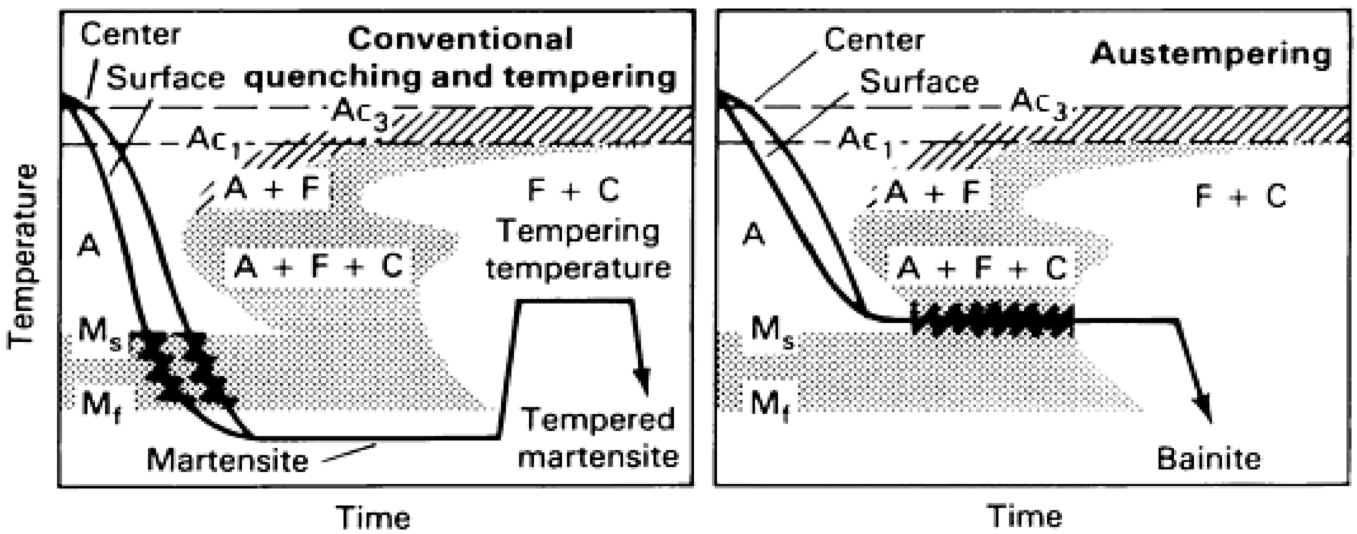


Figure 3-10 Comparison of time-temperature transformation cycles for conventional quenching and tempering and for austempering (A=Austenite=ferrite & C=cementite) [9]

Austempering is particularly advantageous for the heat treatment of thin sections of plain carbon steels to produce excellent toughness and ductility at a hardness of about Rockwell C50. From the table (3.1) it can be seen how the austempering increases the impact strength and ductility in 1095 AISI steel.

The reason for the increase in these properties is attributed to the favorable iron-carbide distribution in the bainitic structure [16].

Table 3-1 Effect of austempering on mechanical properties of steel [12]

Property measured	Quench and Temper	Austempering
Rockwell C hardness	49.8	50.0
Ultimate tensile strength, Mpa	1.76×10^4	1.76×10^4
Elongation %	3.75	5.0
Reduction in area %	26.1	36.6
Impact (J) (un-notched round specimen)	19.0	49
Free-bend test	Ruptures at 45^0	Greater than 150^0 without rupture

Steel composition
0.78%C;0.58%Mn;0.146 Si; 0.0425 P;0.0405 S

Quench & temper	**Austempering**
Pb bath 750 C^0, 5 min.	Pb bath 750 C^0, 5 min.
Oil quench	Transformed in Pb-Bi bath at 310 C^0, 20 min.
Tempered 350 C^0, 30 min	

Austempering process, however, has its limitations and is impractical to use for some steels. In order to obtain a uniform structure and hence uniform mechanical properties, the entire cross section of the steel must be cooled rapidly enough to miss the nose of the IT curve. In plain carbon steels, only relatively thin sections can be austempered since the time of start the austenite-to-bainite transformation near the nose of the IT diagram for plain carbon steels is so short. With some alloy steels, larger cross sections can be austempered since the time to start the transformation is much longer. However, if the time to start the transformation becomes too long, the process becomes time consuming to be practical [12].

3.2.1.10 Martempering (marquenching)

Martempering is a modified quenching procedure used for steels primarily to minimize distortion of the heat- treated material. The martempering process consists of (a) austenizing the steel, (b) quenching it in hot oil or molten salt at a temperature just slightly above (or slightly below) the martensite start temperature (c) holding it in the quenching medium until the temperature is uniform throughout the steel (the isothermal treatment is normally stopped before the transformation of the austenite-to-bainite reaction begins), and (d) cooling at a moderate rate to prevent drastic temperature differences between the surface and core of the steel. Figure (3.11) shows cooling curves for martempering and modified martempering of eutectoid plain carbon steels. Martempered steels are usually tempered later to toughen the steel. In martempering, by allowing the martensitic transformation to take place at higher temperatures than used for conventional quenching, distortion and residual stresses in the work piece are reduced. Table (3.2) Campers the mechanical properties of 1095(AISI) steel after martempering and tempered with those after conventional quenching and tempering at Rockwell hardness of about C50 [4].

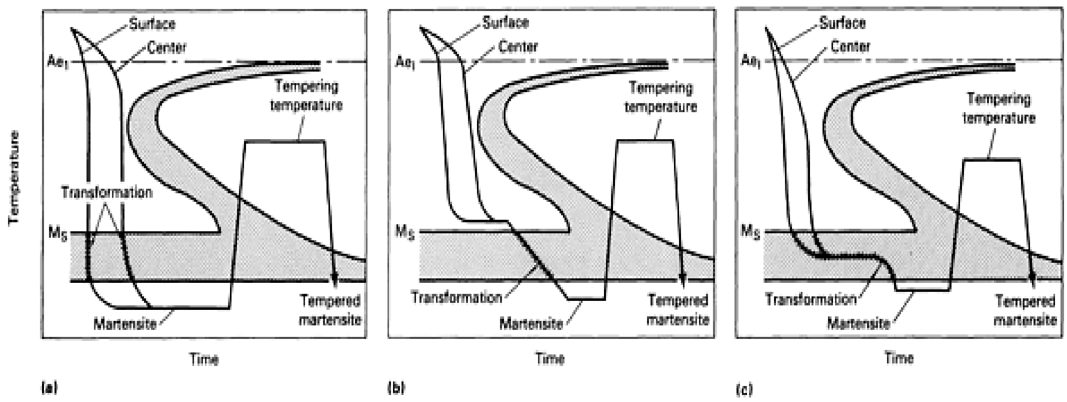


Figure 3-11 Time temperature transformation diagrams with superimposed cooling curves showing quenching and tempering. (a) Conventional process. (b) Martempering. (c) Modified martempering [9]

Table 3-2 Effect of martempering on mechanical properties of steel [12]

Heat treatment	Rockwell C hardness	Impact J	Elongation %
Martempered and temper	53	38	0
Water quench and temper	53	16	0

3.2.1.11 Subzero treatment (deep freezing)

Sub-zero treatment allows maintaining a certain structure or to induce or prolong a structural transformation, this treatment is mainly used for the transformation of residual austenite after hardening, e.g. In the case of measuring equipment, to obtain maximum dimensional stability. Sub-zero treatment can be carried out with cooled air (deep freezing unites for cooling to approximately -80 ^{0}C down to -140 ^{0}C). In general, however, temperature below -80 ^{0}C is produced by dry ice, alcohol mixtures or liquefied gases (e.g. liquid nitrogen -190 ^{0}C) figure (3.12) [13] .

3.2.1.12 Hot forming

By definition, through heating for the purpose of hot forming is not regarded as heat treatment although it is basically done in the same way as through heating to austenitizing temperature. The start of deformation should be selected in a way that deformation is finished at lower temperature limit in order to avoid coarse grain formation.

In certain cases under certain conditions, hot forming may be immediately followed by a heat treatment process (e.g. hardening from hot forming temperature without intermediate cooling to below AC_1. The combination of hot forming and heat treatment processes is also used sometimes to obtain specific material properties. These thermomechanical treatments include for example the ausforming process which consisting of austenitizing, cooling to a temperature range within which transformation tendency is low, hot forming without recrystallization, further quenching for the purpose of hardness increase [15] .

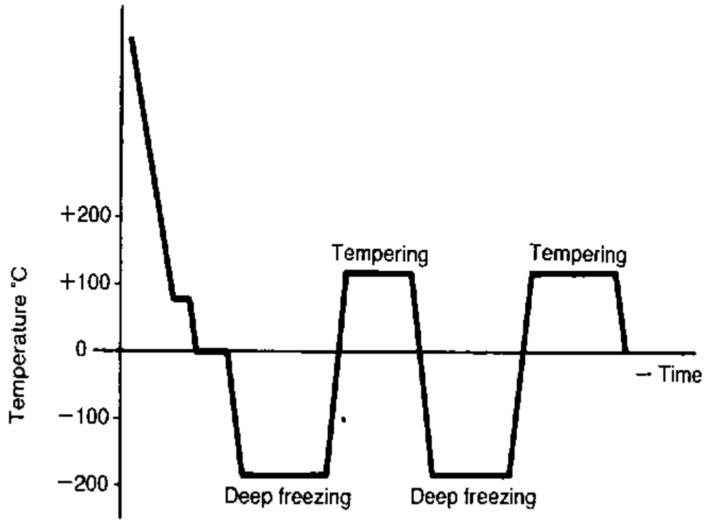


Figure 3-12 Example of sub-zero treatment procedure

3.2.2 Surface hardening

The surface of numerous construction elements such as crank shafts, cogged wheels or camshafts are exposed to wear. These components require a high extent of surface hardness with a tough core at the same time. One possibility to obtain such a state is to austenitized the surface of heat-treatable steels and to quench it afterwards.

Heating will be carried out by:

- **Gas flame (flame hardening):** heating by gas torches as shown figure (3.13)
- **High-frequent current (induction hardening):** heating by induction eddy currents which are produced by the alternating electromagnetic field of a current passing through a heating inductor as shown in figure (3.14)

  Quenching is often carried out using a water shower. In the process, only a very thin surface layer is brought to austenitizing temperature and hardened by immediately following rapid cooling, normally in water, aqueous solutions or oil emulsions. because of the short time of heating , the hardening temperature are normally approx. 30-100 ^{0}C higher than in conventional hardening or tempering operations. Depending on the steel grade (usually unalloyed heat treating steels specially suited for surface hardening) and on the carbon content, a surface hardness of 50 to 65 HRC can be obtained. The depth of hardening (approx. 1-15 mm) is dependent on the content of alloying constituents and on the heating and hardening conditions (feed rate and torch size or frequency). The properties of the core are left unchanged.

The processes are used to harden gear teeth, spindles, crankshafts, connecting rods, camshafts, sprockets and gears, shear blades and bearing surfaces [17].

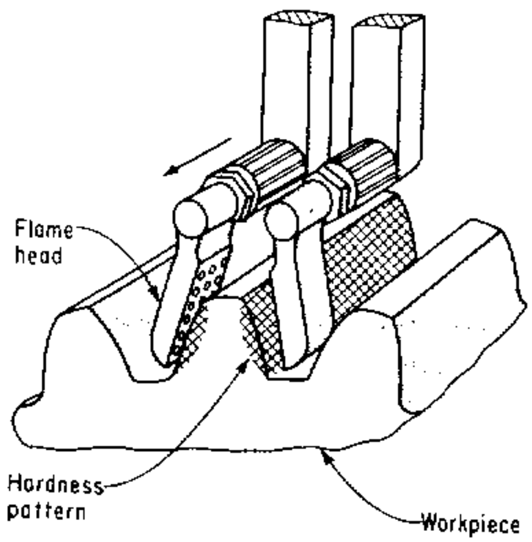


Figure 3-13 Progressive method of flame hardening [12]

3.2.3 Thermo-chemical treatment

This treatment is generally takes place by diffusion process by adding one or more of elements on the steel surface to get the required hardness level and depth.

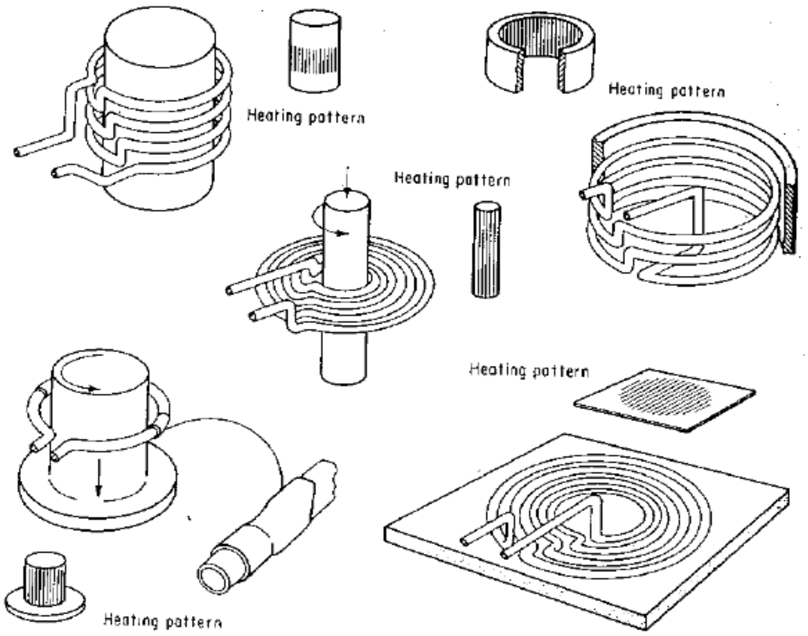


Figure 3-14 Typical works coils for high-frequency units and the heat patterns developed by each [12]

3.2.3.1 Carburizing and Carbonitriding

In carburizing, additional carbon is diffused into the surface of a low-carbon steel to give a high-carbon surface layer. When this is quenched, the layer transforms to a hard, brittle, martensite, which can subsequently be tempered to obtain the required balance of hardness and toughness. There are three classes of carburizing equipment; all require temperatures of about 900 to 950 ^{0}C. The first uses a powder pack that releases carbon monoxide (CO); this decomposes on the surface of the steel to give atomic carbon and CO2. It is best for small parts [12]. The second uses a fused salt bath containing sodium cyanide (NaCN more than 25%), barium chloride, sodium chloride and accelerators; it is very versatile and inexpensive process. The last uses gas-methane, butane or pentane-as the source of carbon in a special muffle furnace that allows the gas to flow freely round the parts to be carburized; it lends itself to large-quantity production. The most favourable carbon content for surface layer hardenability is approx.

0.60-0.80 %. The carburizing depth is influenced by the carburizing temperature and time figure (3.15). The term depth of carburization denotes the vertical distance from the surface of a carburized work piece to that point at which the carbon content still meets a preset limit 0.30 %, which is meets 550 HV1 according to DIN 50190/part 1, figure (3.16) [15].

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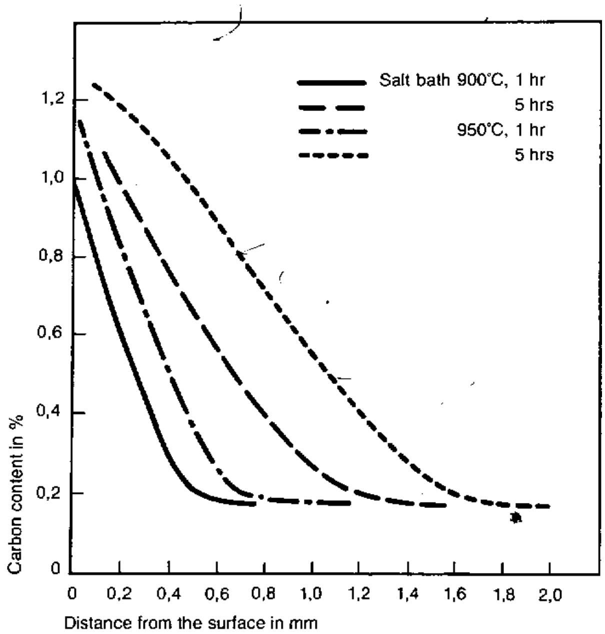


Figure 3-15 Carburization for 16MnCr5 (Din) [9]

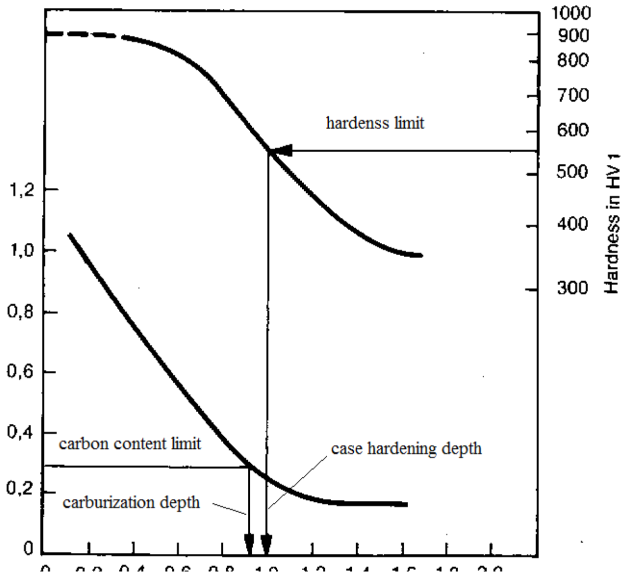


Figure 3-16 Correlation between depths of carburization [10]

The recent trends in carburizing are:

- Vacuum carburizing: the components to be carburized are first placed in the heating chamber kept in a tray, and the furnace is then evacuated. The work is thereafter heated in the furnace to the carburizing temperature (1000-1050 ^{0}C). At this stage, a controlled amount of hydrocarbon gas introduced into the furnace with supply pressure in the range of 50-200 m bar.
- Plasma carburizing: in plasma carburizing, carbon is imparted to the surface of the steel by the impingement of carbon ions escaping from an ionized gas or plasma. The work piece to be treated is heated to a carburizing temperature (1040-1050 ^{0}C) in a vacuum, with subsequent introduction of a small volume of carbon bearing gas. [9]

  After carburization, case hardening steel represents practically two different steels (surface layer with a carbon content of approx. 0.8 % and core with a carbon content of approx. 0.2 %) with different hardening temperatures. This must be dully considered during hardening. Depending on material, shape, size and type of stress, the component can be subjects to different case hardening treatments [11].

  - **Direct hardening:** this is the most economical type of heat treatment with the lowest amount of distortion.
  - **Double quench hardening:** the first hardening process takes place from the core hardening temperature and the second one from the surface hardening temperature which is now rarely used, normally; the first hardening treatment takes place directly from carburizing temperature.

The selection of case hardening steels is determined by the required care properties. For simple components which require only wear resistance, unalloyed or chromium alloyed steels will do. If dynamic stresses such as tensile, compressive, bending or tension stresses are also involved, steels with higher core strength the required (Cr-Mo-Cr-Mn steels). If more severe impact stresses and short-time overstressing is expected, steels with higher toughness (Ni, Cr-Ni, Cr-Ni-Mo steels) must be selected.

Carbonitriding is a variant of gas carburizing in which ammonia (NH_3) is added to the carburizing gas. Nitrogen from the ammonia, and carbon from the carburizing gas, diffuses into the component at the same time, precipitating nitrides as well as increasing the surface carbon content. It generally required a lower temperature and shorter time than plain carburizing. The process produces a thinner layer, but one that retains its hardness to higher temperatures.

Both processes give components with hard, wear resistance surfaces on a tough, ductile core. Carburizing gives better impact resistance than carbonitriding, but it causes more distortion and is slower, making it more expensive [10].

Typical uses: Automotive, mechanical engineering, aeronautical engineering, rod, gears, mandrel, shafts, transmission gears, and camshafts [4].

3.2.3.2 Nitriding and Nitrocarburizing

In nitriding, nitrogen is introduced into the surface of a steel component by thermochemical treatment at a temperature below AC_1 in the ferrite phase. The temperature from (495 to 565 ^{0}C) is lower than that for carburizing, giving less distortion, and the surface does not require later heat treatment as carburizing does. Nitriding gives a high surface hardness, retained to high temperatures, increased wear resistance, improved fatigue life, and enhanced corrosion resistance.

Nitriding causes the materials thickness to increase by approx. 0.02 to 0.03 mm. Depending on the type of nitriding medium , nitriding can be carried in gas containing cracked ammonia (NH_3), salt bath typically, sodium cyanide (NaCN) ,or plasma (under vacuum) environments [4] .

Nitriding is most effective when applied to steels containing nitride forming elements such as aluminum, vanadium, tungsten, chromium, or molybdenum. The process can also be stainless steels, some tool steels and certain cast irons. Ideally, steels for nitriding should be in the hardened and tempered condition, requiring that the tempering temperature be higher than nitriding temperature. A fine turned or ground surface finish is best.

In Nitrocarburizing process the surface layer of the component will be consists of nitrogen which is the main element to make nitrides and carbon, and the temperature is between 550 to 580 ^{0}C and the time is less than the gas nitriding process [11].

Typical uses:

Nitriding is widely used in automotive, mechanical and aeronautical engineering. Typical component are gears, crankshafts, camshafts, valve parts, extruder screws, forging dies, aluminium extrusion dies, injectors and plastic mould tools [4].

3.2.3.3 Gas Nitriding

Highest surface hardness values are reaches by steels containing a sufficient amount of special of nitride-forming elements. Figure (3.17) shows the variation of hardness and depth of different steels.

The gas nitriding process is normally carried out at temperatures between 490 and 520 ^{0}C in a stream of ammonia. The nitriding time which determines the depth of nitriding (vertical distance from the surface to the point at which the hardness still reaches a preset limit) is 20 to 60 hours, figure (3.18).

Prior to nitriding, the internal stresses of the work piece should be as low as possible, and their surface should be free of grease [12].

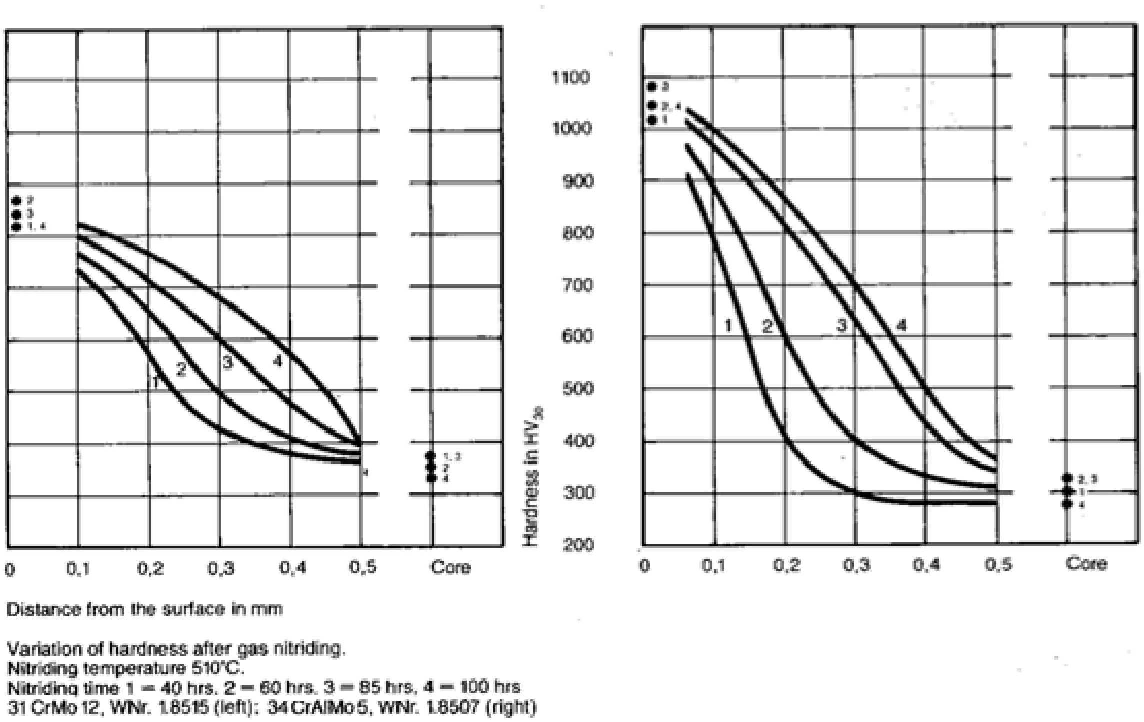


Figure 3-17 Hardness and depth of hardness for different steels after nitriding [9]

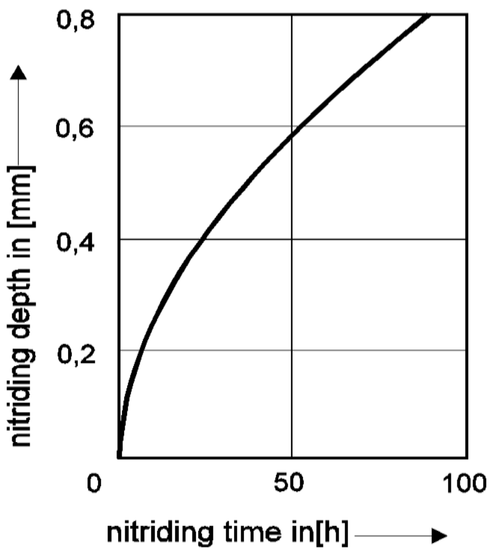


Figure 3-18 Nitriding depth depending on the nitriding time [9]

3.2.3.4 Salt bath Nitriding (Cyaniding)

In cyaniding, the case will contain both carbon and nitrogen and they are produced in liquid salt baths and the proportion of carbon and nitrogen in the case depends on both composition and temperature of the bath.

A special type of salt bath nitriding which uses a titanium crucible with ventilation for adjusting the cyanide/cyanate ratio necessary for obtaining good nitriding results. The nitriding temperature is approx. 570 ^{0}C; the Nitriding times are normally between 30 minutes and 2 hours. In the case of high speed steels it's only few minutes. Quenching after nitriding can be carried out in water, oil, air, vacuum or inert gas but also it can be in a special quenching bath. This process is now rarely used now because of environments problems of cyanide baths [13].

3.3 Weldability of steels

3.3.1 Definition of welding process

Welding is the uniting of materials in the welding zone by the application of heat and/or pressure, with or without the addition of filler material. Auxiliary materials e.g. shielding gases, flux or pastes, may be used to make the process possible or to make it easier. The energy required for welding is supplied from outside sources.

Welding processes are classified on the basis of the energy transfer medium operating on the work piece from outside sources, the nature of the parent material, the purpose of welding, the physical process occurring during welding and the type of manufacture.

3.3.2 Areas of applications in welding engineering

There are many applications that can be used the welding processes especially in the industrial field, which include:

- Mechanical engineering.
- Road and railway vehicle engineering.

- Aircraft engineering.
- Steel construction.
- Water engineering.
- Boiler, tank- and pipeline engineering.
- Instrument engineering.
- Shipbuilding industry.
- Electronically production.
- Other manufacturing branches.

3.3.3 Selection of the right welding technique

One of the most important requirements should be taken in consideration is to define the factors that control each welding technique, such as:

- Geometry of the component.
- Material.
- Accessibility.
- Number of items.
- Equipment.
- Welding position.
- Requirements.
- Profitability.

3.3.4 Weldability

A component consisting of metallic material is considered to be weldable by a given process when metallic continuity can be obtained by welding using a suitable welding method. At the same time the welds must comply with the requirements specified in regard to both their local properties and their influence on the construction of which they form a part. Weldability is influenced by three factors, namely material, construction and production, which are essentially of equal importance for weldability as shown in figure (3.19).

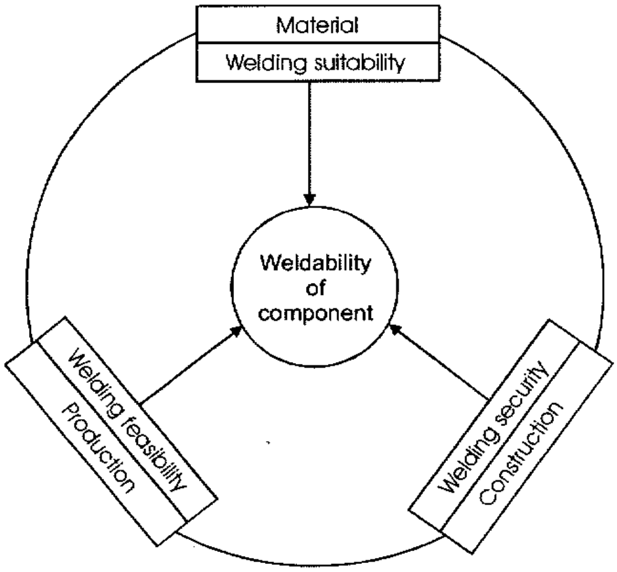


Figure 3-19 Weldability as the resultant of the parameters material, structure and manufacture [9]

3.3.5 The main parameters for Weldability

The steel weldability is depends on many factors such as the chemical composition of steel, cooling rate and the electrode type for metallic arc welding, and the followings are the main parameters to define the weldability:

a) Suitability for welding:

- Chemical composition.
- Metallurgical properties.
- Physical properties.

b) Welding safety:

- Structural design.
- State of stresses.

c) Possibility for welding:

- Preparation for welding.

- Execution of the welding works.
- Post-treatment.

For steel the cooling rate depends on the amount of metal which can conduct heat away from the weld junction (called the Thermal Severity Number) and on the degree of preheat.

The higher the carbon equivalent and the higher the thermal Severity number (TSN) the greater is the necessary to preheat and the higher must be the pre-heat temperature.

To determine the weldability of steel, which consists of several elements, the carbon equivalent (*Ceq*) is calculated by using different equations.

For low alloy steel, elements are expressed in weight percent amounts:

$$Ceq = C + \frac{Mn + Si}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$ **Equation 3-1**

For modern low carbon steels or micro-alloy steels, elements are expressed in weight percent amounts:

$$Ceq = C + \frac{Si}{25} + \frac{Mn + Cr}{16} + \frac{Cr + Ni + Mo}{20} + \frac{V}{15}$$ **Equation 3-2**

The common formula (as in ASM metal handbook, Vol. 6) is as follows:

$$Ceq = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4}$$ **Equation 3-3**

- For (Ceq %< 0.14), excellent weldability and no special precautions necessary.
- For (0.14<Ceq %< 0.45) martensite is more likely to form, and modest preheats with low hydrogen electrodes become necessary.
- For (Ceq %> 0.45) extreme complications, weld cracking is very likely, hence preheat in the range 100-400°C and low hydrogen electrodes are required.

Chapter 4

4 MATERIAL SELECTION

4.1 Introduction of material selection

A designer engineer is faced with two important responsibilities in the evaluation of a product from concept to completion. They are material selection and understanding fabrication process associated with design.

A primary design requirement in the selection of a material for a specific application is that the material be capable of meeting the design service life at least cost.

Selection of a particular material from candidate materials, chosen from available choices is usually made from past experience with similar materials. Advances in technology are demanding better performance from engineering material. Selection of proper engineering material for a given application requires a broad knowledge of the stat of art in materials' development.

Material properties and characteristics play important role in meeting design requirement. It is essential that selection criteria to be established by the designer for the given application [17].

4.2 Selection process

Selection process is affected by (a) choice of material restricted by service requirements, and (b) many materials which could be considered possible contenders to meet design specification. There will be no perfect solution; but several alliterative viable solutions can be achieved. The solution can be arrived at by optimization process.

In order to take informed decision two things are necessary, (1) reliable property data on material and (2) service condition that component or assembly is exposed to operate under.

Reliable property data on material in the case of metals and alloys are standardized through commercial alloy composition and specification internationally.

Service conditions which a component or assembly has to operate requires considerable skill and experience of design and materials engineers. Hence the selection of suitable material to fit requirement often involves compromise with a trade off between properties [18].

A systematic approach to selection process is through optimization. It is of extreme importance for engineer to able to determine which is the most important property to satisfy a particular design.

For any material selection, the designer should comply with the following steps for optimum selection:

a. Analyze product specification and determine acceptable values (criteria) for all relevant material properties.
b. Selection by elimination of all materials which do not posses acceptable criteria.
c. Asses the degree of relative importance of various properties from essential through desirable properties and for each property places the potential materials in ranking order.
d. Evaluate the materials and process costs for each material.
e. Optimize combination of properties evaluated in steps c and d for least cost.

4.3 Optimization of material selection methods:

Several quantitative methods for selection optimization can be applied to choose right material for right application. It should be emphasized at this stage that none of these methods is meant to replace the judgment and experience of the engineer. The methods are only meant to help the designer in ensuring that none of the viable solution is neglected and in making sounder choices and trade-offs for a given application.

4.3.1 Materials charts

The most time-consuming task is the selection of materials is the collection of the information on their properties to match the requirements and constraints of the design [17].

Ashby's (1989) materials selection charts are useful for these purposes, where some of this information is compactly summarized in material charts. These charts were developed by Ashby and are meant only to use at the conceptual stage of selection of materials [18].

Figures (4.1) and (4.2) are simplified versions of two of Ashby's materials charts, which are plots of density versus strength for selection of light, strong materials, and density versus modulus for the selection of light, stiff materials, respectively. The charts show that the properties of each of the different classes of materials are clustered together and are shown within envelops or fields in the charts [19].

Depending upon the geometry and type of loading, different E-ρ and S-ρ relationships apply.

For simple axial loading, the relationship is E/ρ or S/ρ. For loading condition that could lead to buckling, E^2/ρ applies, and for bending of a wide plate the relationship $E^{1/3}/\rho$ applies [18]. Table (4.1) illustrate the variety of the maximizing factors for maximum stiffness and maximum strength for least weight of a material. The table is just small part of many more tables for other properties.

Table 4-1 Combined properties to maximize efficiency or performance indices [17]

Component shape and mode of loading	For stiffness	For strength
Bar-Tensile axial loading- load, stiffness, length specified, section area variable	$\frac{E}{\rho}$	$\frac{\sigma_y}{\rho}$
Tension bar or tube- torque, stiffness, length specified, section area variable	$\frac{G^{1/2}}{\rho}$	$\frac{\sigma_y^{2/3}}{\rho}$
Beam- externally loaded or by self-weight in bending; stiffness, length specified, section area variable	$\frac{E^{1/2}}{\rho}$	$\frac{\sigma_y^{2/3}}{\rho}$
Column- Axial compression-elastic buckling or plastic compression; compression load and length specified; variable section area	$\frac{E^{1/2}}{\rho}$	$\frac{\sigma_c}{\rho}$
Plate- externally loaded or by self-weight in bending; stiffness, length, and width are specified; thickness is variable.	$\frac{E^{1/3}}{\rho}$	$\frac{\sigma_y^{1/2}}{\rho}$

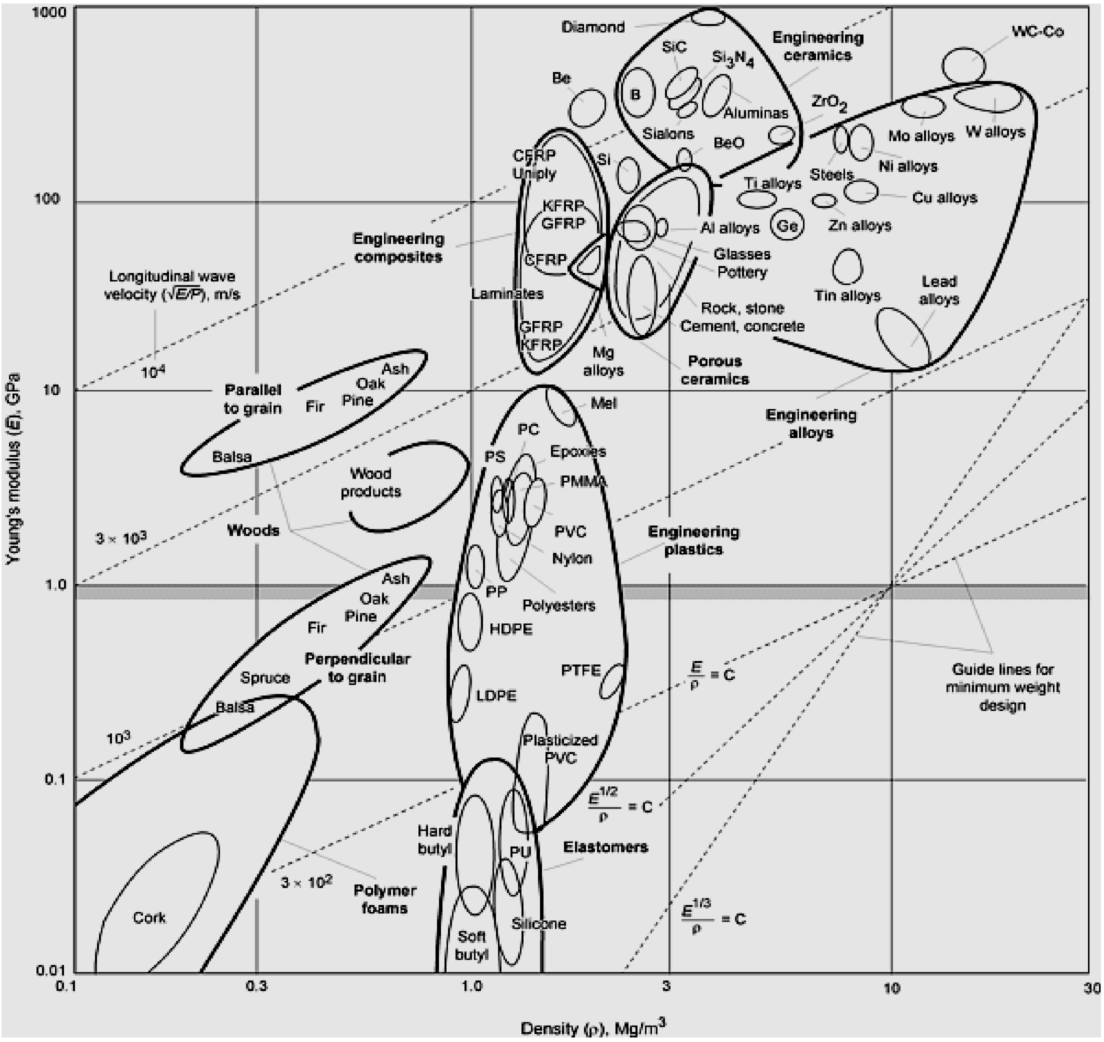


Figure 4-1 Young's modulus, E, plotted against density, for various engineered materials. The heavy envelopes enclose data for a given class of material; the guide lines of constant E/ρ, E $^{1/2}$/ρ and E $^{1/3}$/ρ allow selection of materials for minimum weight, deflection-limited, Design [20]

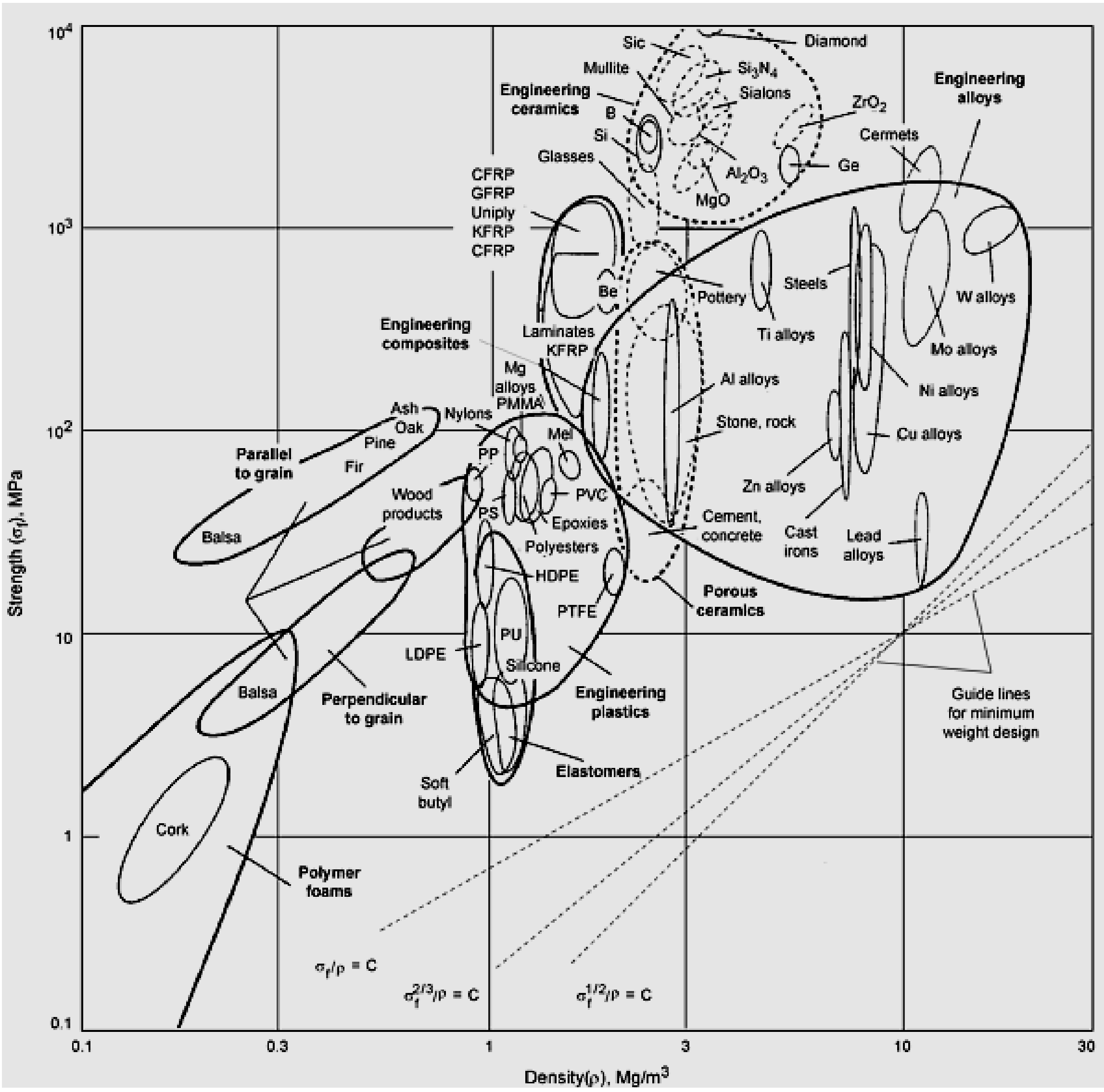


Figure 4-2 Strength, f, plotted against density for various engineered materials. Strength is yield strength for metals and polymers, compressive strength for ceramics, tear strength for elastomers, and tensile strength for composites. The guide lines of constant σ_f/ρ, $\sigma_f^{2/3}/\rho$, and $\sigma_f^{1/2}/\rho$ are used in minimum weight, yield-limited, design [20]

4.3.2 Cost per unit property method

It's the simplest cases of optimizing the selection of materials, one property stand out as the most critical service requirement. In such simple cases, the cost per unit property can be used as a criterion for selecting the optimum material.

In comparing different candidate materials, only cost of unit strength needs to be compared. The material with lowest cost per unit strength is the optimum materials [19].

Although the cost per unit property method can be useful in optimizing simple cases of selection, it has the drawback of considering one requirement only as the most critical and ignoring other requirements. In many engineering applications, the situation is more complicated than this and material requirements usually specify more than one property as being important.

4.3.3 Limits on properties method

In the limits on properties method, the performance requirements are divided into three categories:

- Lower limit properties.
- Upper limit properties.
- Target value properties.

The limit on properties method is usually suitable for optimizing material and process selection when the number of possible alternative is relatively large. This is because the limits which are specified for different properties can be used for whose properties are above the lower limits, below the upper limits, and within the limits of target values of the respective specified requirements. After the screening stage, the limits on properties method can then be used to optimize the selection from among the remaining materials.

In this method, each performance requirement is assigned a weight factor o, each of the properties of a candidate material is compared with limit set for this property and a merit parameter is then calculated for each material. The merit parameters are compared in order to arrive at the optimum material [18].

In limit on property method, properties should have numerical values to calculate the merit parameter, so properties like weldability, corrosion rate, and wear resistance difficult to condenser them because numerical values are rarely given.

4.3.4 Weighted properties method

The weighted properties method can be used for selecting materials when several properties should be taken in consideration. In this method each material property is given a certain value or weight according to its importance.

A weighted property value can be obtained by multiplying the actual values of the material property by the weighting factor (α). Then material performance index (γ) is obtained by summed individual weighted property values of each material. The material with highest performance index (γ) is considered as the optimum for the application.

In its simple form, the weighted properties method has the drawback of having to combine unlike units, which could yield irrational results. Sometimes there is a big numerical difference in properties this will make the property with higher numerical value will have more influence than is warranted by its weighting factor.

By introducing scaling factors & each property will be scaled where the highest numerical value does not exceed 100. When evaluating a list of candidate materials, one property is considered at a time. The best value in the list is rated as 100 and the others normal are scaled proportionally. So, scaling factor will make normal material property values to scaled dimensionless values. For a given property the scaled value (B) for a given candidate steel is equal to:

$$B = \textit{Scaled}\ \text{Property} = \frac{\text{Numerical value of property} \times 100}{\text{Maximum value in the list}} \qquad \textbf{Equation 4-1}$$

For properties like cost, corrosion or wear loss, etc., a lower value is more desirable. In such case the lowest value is rated as 100 and B is calculated as:

$$B = \textit{Scaled}\ \text{Property} = \frac{\text{Minimum value in the list} \times 100}{\text{Numerical value of property}} \qquad \textbf{Equation 4-2}$$

For material properties that can be represented by numerical values, application of the above produce is simple. However, with properties like wear resistance, machinability and weldability, etc., numerical values are rarely given and materials are usually rated as very good, good, fair, poor, etc. in such cases the rating can be converted to numerical values using an arbitrary scale (5, 4, 3, 2, and 1 respectively). Then

$$\text{Materail performance index } (\gamma) = \sum_{i=1}^{n} \text{Bi}\ \alpha\text{i} \qquad \textbf{Equation 4-3}$$

Where (i) is summed over all the n relevant properties. In the cases where numerous material properties are specified and the relative importance of each property is not clear determinations of the weighting factors, (α) can be largely intuitive which reduces the reliability of selection. This problem can be solved by adopting a systematic approach to the determination of (α). The digital logic approach can be used as a systematic tool to determine (α). In this procedure evaluations are arranged such that only two properties are considered at a time. Every possible combination of properties or performance goals is compared and no shades of choice are required only a yes or no decision for each evaluation. To determine the relative importance of each property or goal a table is constructed the properties or goals are listed in the left-hand column and comparisons are made in the columns to the right as shown in table (4.2), where five properties or goals are considered.

In comparing two properties or performance goals the more important goals is given numerical one (1) and the less important is given zero (0). The total number of possible decision N=n (n-1) / 2 where n is the number of properties or goals under consideration. A relative emphasis coefficient or weighting factor (α) for each goal is obtaining by dividing the number of positive decisions for each goal (m) into the total number of possible decisions (N). In this case is $\sum \alpha = 1.0$.

Cost (stock material, processing, finishing, etc) can be considered as one of the properties and given the appropriate weighting factor.

Then, results will be shown as in table (4.3) [17].

Table 4-2 Determination of the relative importance of performance goals using the digital logic method.

Goals	Number of possible decisions [N= n(n-1)/2]										Positive decisions	Weighting factor (α)
	1	2	3	4	5	6	7	8	9	10		
1	1	1	0	1							3	$\alpha_1 = 0.3$
2	0				1	0	1				2	$\alpha_1 = 0.2$
3		0			0			1	0		1	$\alpha_1 = 0.1$
4			1			1		0	1		2	$\alpha_1 = 0.2$
5				0			0		1	1	2	$\alpha_1 = 0.2$
	Total number of positive decisions										= 10	$\sum \alpha = 1.0$

Table 4-3 Scaled values of properties and performance index

Material	Scaled properties					Performance index (γ)	Rank
	1	2	3	4	5	$\sum B_i$	
X1	B1	B2	B3	B4	B5	γ (x1)	2
X2	B1	B2	B3	B4	B5	γ (x2)	1 (highest γ)
X3	B1	B2	B3	B4	B5	γ (x3)	3 (lowest γ)

4.4 Material selection for machine design

Materials selection is a part of engineering process whether you design the machine or if somebody else designs the machine. All the factors that would go into your own design should also be considered when evaluating someone else's design if it is your responsibility to make the piece of equipment function.

The materials selection process should be started as early as possible in a machine design. The key to proper material selection is to establish a checklist of the properties required for a serviceable design. Does the part have to be hard? Does it require wear resistance? Once the required use properties are established, designer can draw on their repertoire of available engineering materials to select one or more candidate materials and treatments. In this point it is appropriate to compare candidate materials for availability and economics. The final selection will be a compromise of properties, availability, and economics, but in no case should serviceability be compromised.

Designer should consider the following points:

A. Consider materials of construction concurrent with design ideas.
B. Look all costs of using a material, not just the cost per unit volume. Fabrication costs often outweigh raw materials costs.
C. Thoroughly consider the properties that are important to a design use these as the basis of selection.
D. Use complete specifications for materials, and treatments [18].

4.4.1 Mechanical properties required for machine design

Mechanical properties are of foremost importance in selection materials for structural machine components, like tools, any power transmission device, and any wear member. Figure (4.3) shows the most mechanical required for machine design [4].

Capacity of a machine component is related to most severe condition it can sustain without a change that will prevent the component from containing its intended function. In most cases, sustaining loads is the main manifestation of capacity.

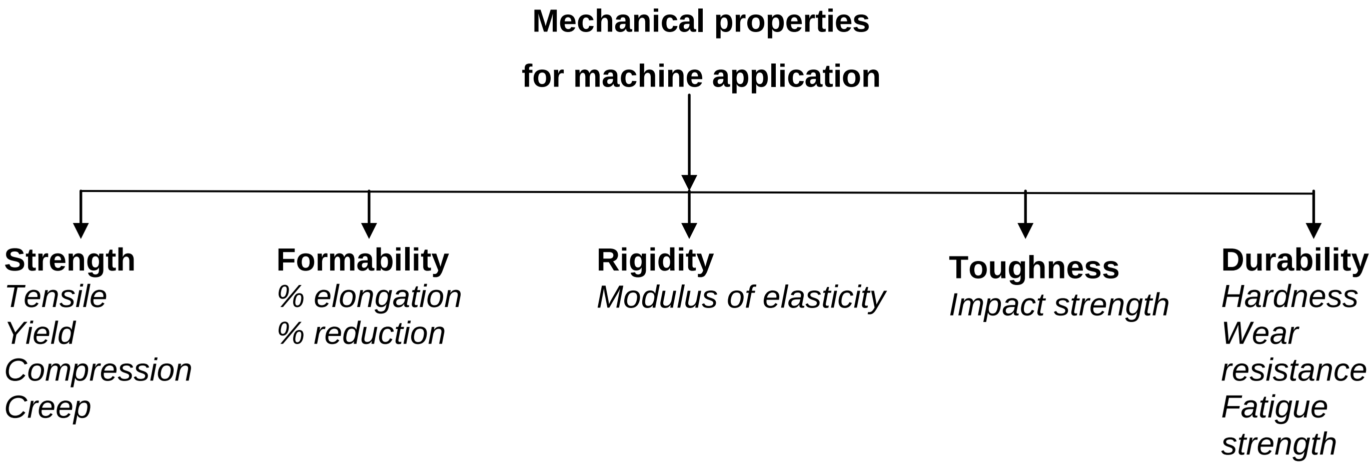


Figure 4-3 Mechanical properties required for machine design

4.4.2 Selection of materials for static strength

Static strength is the resistance a short term steady load at moderate temperatures. This resistance is usually measured in terms of yield strength, ultimate tensile strength, compressive strength, and hardness. Ductile metallic materials are strong in tension and compression but brittle are stronger in compression than in tension.

Most of engineering materials are isotropic but some are anisotropy, where the strength depends on the direction in which it is measured. The anisotropy degree is depends on the nature of the material properties and its manufacturing history. For wrought metallic materials (such as steels) anisotropy is more clear when elongated inclusions are found in the matrix and when processing consists of repeated deformation in the same direction [18].

The level of strength of engineering materials may be viewed either in absolute terms or relative to similar materials.

From the design point of view, it is more convenient to consider the strength of the materials in absolute terms. From the manufacturing point of view it is important to consider the strength as indication of the degree of development of the material concerned, i.e. relative to similar materials.

The low strength materials are usually used to meet requirements other than strength such as corrosion resistance or cost which are more important than high strength. Medium strength materials are usually more widely used because they combine good strength, ease of manufacture, and economy. Highly strength materials are most expensive, but this could result in reduction of the total cost of the finished component, because the amount of materials used would be less and then total cost could also be less.

Some materials can increase their strength by using heat treatment process like normalizing and hardening, but this will increase also the total cost [19].

4.4.3 Selection of materials for stiffness

When a load is placed on a beam, the beam is bent and every portion of it is moved in a direction parallel to the direction of the load. The distance that a point on the beam moves, deflection, depends on its position in the beam, the type of beam, and the type of supports. For example, a beam which is simply supported at both ends suffers maximum deflection in its middle when subjected to a concentrated central load. The deflection of the beam under load can be taken as a measure of stiffens.

In applications where both stiffens and weight of a structure are important. It becomes necessary to consider the stiffness / weight, or specific stiffness, of the structure [17].

4.4.4 Selection of materials for toughness

There is a close relationship between toughness and other mechanical properties. Within a give class of materials, there is an inverse relationship between strength and toughness. Generally, the toughness of a material is influenced by its chemical composition and microstructure, for example, steels become less tough with increasing the carbon content, larger grain size, and more brittle inclusions. The grin size of steels is affected by the element present, especially those used for deoxidizing. Small addition of aluminium to steel is known to promote finer grain size, which improves the toughness. Fully killed fine-grained steels also have lower ductile-brittle transition temperatures and are normally selected for applications where brittle fracture may occur. Fine grains can also be obtained in steels by using alloying elements, by controlling the rolling practice, or normalizing treatment [13].

A thoroughly deoxidized steel grade has a fewer non-metallic inclusions and gives better toughness. When brittle inclusions are elongated, their influence on ductility is more pronounced in the transverse and through-thickness directions [17].

The method of fabrication can also have a pronounced effect on toughness, and experience had shown that a large proportion on brittle fractures originate from welds or their vicinity. This can be caused by the residual stresses generated by the welding process, reduction of toughness of the heat-affected zone, or by defect in the weld area.

The rates of loading application also influence the toughness. Materials which are tough under slowly applied load may behave in a brittle manner when subjected to shock or impact loading. [16]

Decreasing the operating temperature generally causes a decreasing in toughness of most engineering materials. [18].

4.4.5 Selection materials for fatigue resistance

In any engineering application, the behaviour of a component in service is influenced by several other factors besides the properties of the material used in its manufacture. This is particularly true for the cases where the component or structure is subjected to fatigue loading. Under such condition the fatigue resistance can be greatly influenced by the service environment, surface condition of the part, method of fabrication, and design details.

Steels are the most widely used structural materials for fatigue applications as they offer high fatigue strength and good processability at a relative low cost. Steels have the unique characteristic of exhibiting an endurance limit, which enables them to perform indefinitely, without failure, if the applied stresses do not exceed this limit [13].

The optimum steel structure for fatigue resistance is tempered martensite, since it provides maximum homogeneity. Steels with high hardenability give high strength with relatively mild quenching and, hence, low residual stresses, which are desirable in fatigue application. Normalized structures, with their finer structure give better fatigue resistance than the coarse pearlitic structures obtained by annealing.

Inclusions in steel are harmful as they represent discontinuities in the structure that could act as initiation sites for fatigue cracking. Therefore, free-machining steels should not be used for fatigue applications. However, if machinability consideration make it essential to select a free-machining grade, the leaded steels are preferable to those containing sulphur or phosphorus. This is because the rounded lead particles give rise to less structural stress concentrations than the other angular and elongated inclusions [17].

4.4.6 Selection materials for wear resistance

The main factors which influence the wear behaviour of material can be grouped are:

A. Metallurgical variables, including hardness, toughness, chemical component and microstructure.
B. Service variables, including contacting materials, contact pressure, sliding speed, operating temperature, surface finish, lubricating, and corrosion [17].

Although the performance of material under wear conditions is generally affected by its mechanical properties, wear resistance can not always be related to one property. In general, wear resistance does not increase directly with tensile strength or hardness although if other factors are relatively constant, hardness values provide an approximate guide to relative wear behaviour among different materials. This is particularly true for application involving metal-to- metal sliding. In such cases, increasing the hardness increases wear resistance as a result of decreasing penetration, scratching, and deformation. Increasing toughness also increase resistance by making it more difficult to tear off small particles of deformed metal.

Mild steels although among the cheapest and most widely used materials, have poor wear resistance and can suffer severe surface damage during dry sliding. This can be avoided by selecting compatible mating materials. Increasing the carbon content of the steel improves the wear resistance but increases the cost. Surface-hardened carbon or low alloy steels can be another step higher in wear resistance. Components made from these steels can be surface hardened by carburizing, cyaniding, or carbonitriding to achieve better wear resistance at a still higher cost. An even higher wear resistance can be achieved either by nitriding medium-carbon chromium or chromium-aluminium steels, or by surface hardening high-carbon high-chromium steels [13]. Surface treatment avoids having to make the entire part of a wear-resistance material, which may not provide all the other functional requirements or may be more expensive. Surface treatments include:

- Surface heat treatment, as in the case of flame and induction heating which allows hardening of the surface without affecting the bulk of the material, table (4.4).
- Surface alloying, as in the case of carburizing, nitriding, and carbonitriding, which increase the hardness of the surface by increasing its carbon and/ or nitrogen content, table (4.4).

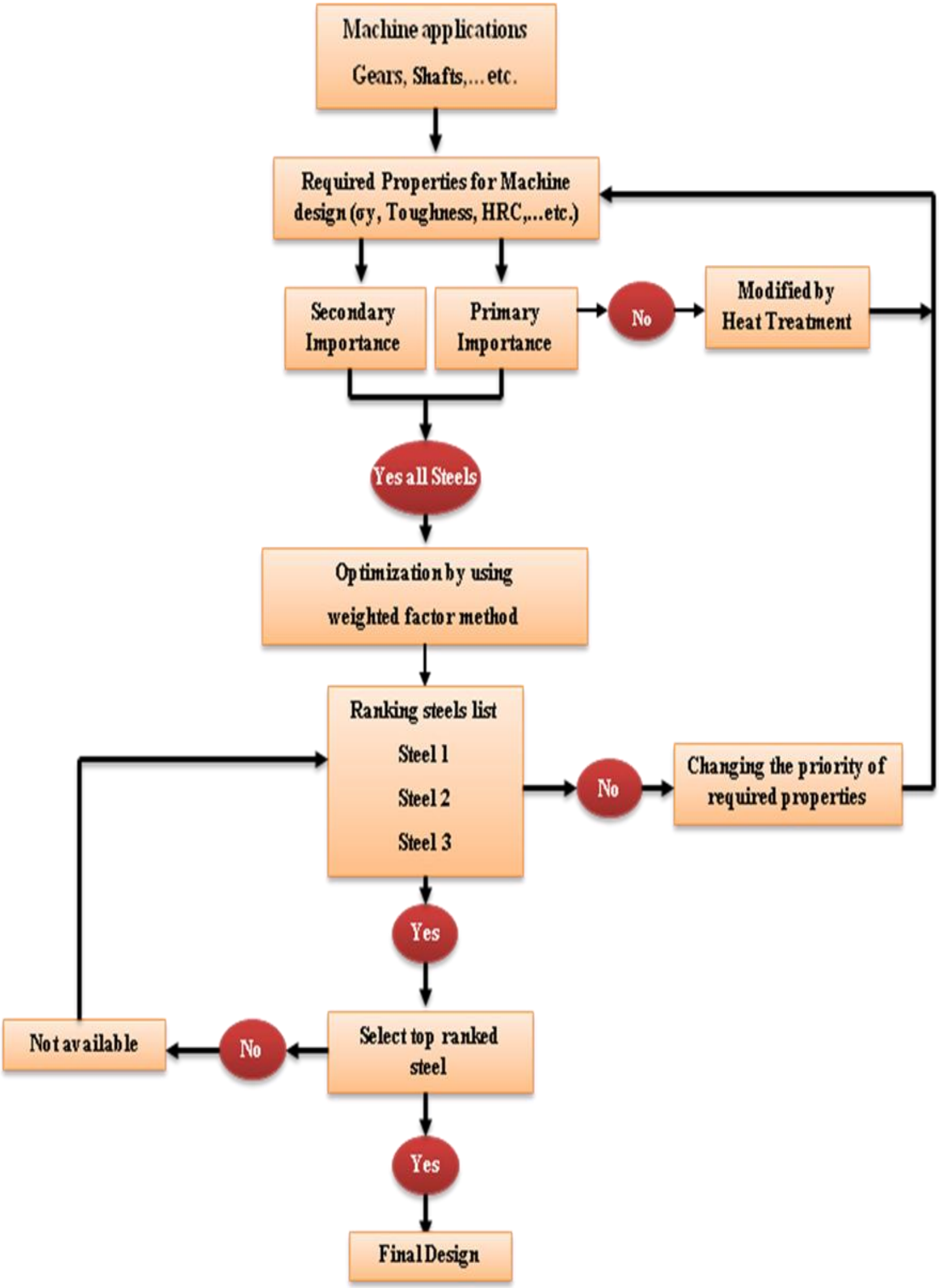
Table 4-4 Surface hardening treatments for steels.

Process	Treatment	Application
Flame hardening	Heat the surface using torch, then quench	Hardened depth is 0.5-6 mm. used for gear teeth, crankshaft, and axles.
Induction hardening	Heat the surface using high-frequency induction current, then quench.	
Carburizing	Heat component at 850-950 ^{0}C in a carbon reach gas or solid, then quench.	Hardened depth is 0.5-1.5 mm. used for gear teeth, cams, shafts, bolts, and nuts.
Cyaniding	Heat component at 700-850 ^{0}C in a cyanide-rich salt bath, e.g. sodium cyanide, then quench	Hardened depth is 0.02-0.3 mm. used for small articles such as small gears, bolts, nuts
Nitriding	Heat component at 500- 650 ^{0}C in ammonia gas	Hardened depth 0.05-0.6 mm. used for gears, bolts, and nuts.
Carbonitriding	Heat component at 700-850 ^{0}C in a mixture of carbon-rich and ammonia gases, then quench.	Hardened depth is 0.05-0.6 mm. used for gears, tools, bolts, and nuts.

4.4.7 Selection of material for low cost

Cost usually are controlling factor in evaluating materials , because in many applications there is a cost limit for a material intended to meet the application requirements. When the cost limit is exceeded, the designer may have to change his selection and use a less expensive material. The cost of processing often exceeds the cost of the stock material.

Flow chart of optimization process of steels for machine application



Chapter 5

5 SELECTION OF GEARS STEELS

5.1 Definition of gear

The gear is a machine element used to transmit motion between rotating shafts ,when the center distance of the shafts is not too large .Toothed gears provide a positive drive, maintaining exact velocity ratios between driving and driven shafts, a factor that may be lacking in the case of friction gearing which is subject to slippage Depending on their construction and arrangement, geared devices can transmit forces at different speeds, torques, or in a different direction, from the power source.

The most common situation is for a gear to mesh with another gear, but a gear can mesh with any device having compatible teeth, such as linear moving racks. The gears most important feature is that gears of unequal sizes (diameters) can be combined to produce a mechanical advantage, so that the rotational speed and torque of the second gear are different from those of the first. Most gears are circular and most shafts joined to the gears are parallel to one another. If the smallest of a gear pair (the pinion) is on the driving shaft, and has half as many teeth as the driven gear, for example, the torque of the driven gear is twice the pinion torque, whereas the pinion speed is twice the speed of the driven gear [21].

5.2 Gear types

- Spur gears: transmit power and motion between parallel axes
- Helical gears: transmit power and motion between parallel axes (opposite hand)
- Bevel gears: operate on intersecting axes which are often at right angles
- Hypoid gears: Similar to a bevel gear, but driven by a worm-like drive on non-intersecting axes.

- Worm gear: drive gear for high ratio speed reduction between non-intersecting right-angle axes
- Rack and pinion: pinions are drive gears use to drive racks or larger gears. They can be physically similar to spur gears, and occasionally helical gears. The "pinion" designation is primarily one to indicate that it is the driving gear in a rack and pinion configuration. Rack is a straight component with gear teeth; typically straight-toothed; mates with pinion (spur gear).
- Internal gear: typically straight teeth on ID with circular OD; mates with spur gear on the inside [21]. Figure (5.1) shows the common gear types.

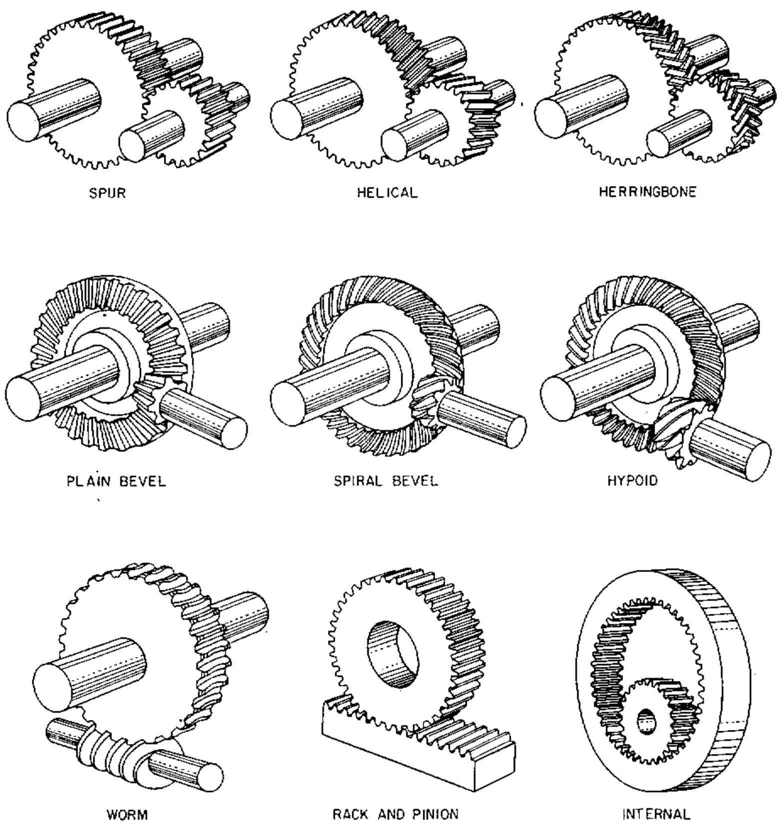


Figure 5-1 Gears type [21]

5.3 Mechanical properties required

5.3.1 Fatigue strength

This property is important as the gears are constantly experiencing varying loading cycles. The fatigue resistance can also be related to the surface hardness of the gear.

5.3.2 Wear resistance

Wear resistance is extremely important in determining the overall life cycle of a gear and its performance. Wear resistance can be related to the surface hardness of the steels.

5.3.3 Surface Hardness

For a gear the surface hardness helps control the wear resistance of the gears and the overall performance and life time.

5.3.4 Toughness

Sometimes designer should consider it as primary requirement when shock loads and heavy sections are subjected.

5.3.5 Machinability

It’s important to minimize the overall cost of the manufacturing.

5.4 Steels for gears

There are a number of steels used for gears, ranging from plain carbon steels through the highly alloyed steels and from low to high carbon content. The selection of steels will depend upon many factors including mechanical properties and service.

Steel has the outstanding characteristic of high strength per unit volume and low cost. There are primary reasons that steels gears are used predominantly in industry. Furthermore the vast majority of gears made from either plain carbon or alloy steels are heat treatment to increase strength and life, although both plain carbon and alloy steels with equal hardness exhibit equal tensile strength. Alloy steels are preferred because of higher hardenability and desired microstructures of the hardened case and core needed for high fatigue strength of gears.

The size of the gear should be considered when selecting the steels of gears as well as its service requirements.

Gear steels may be divided into two general classes: plain carbon and alloy steels. Alloy steels are used to some extent in the industrial filed, but heat treated plain carbon steels are far more common. The use of untreated alloy steels for gears is seldom, if ever justified and then only when heat treating facilities are lacking [21]. The gears steels grads and chemical composition are given in Table (5.1).

The point to considered in determining whether to use heat treated plain carbon steels or heat treated alloy steels are: (1) Does the service condition or design require the superior characteristics of alloy steels? (2) If alloy steels are not required, will the advantages to be derived offset the additional cost? For most applications, plain carbon steels, heat treated to obtain the best of their qualities for the service intended, are satisfactory and quit economical [22].

The advantages obtained form using heat treated alloy steels in place of heat treated plain carbon steels are as follows:

1. Increased surface hardness and depth of hardness penetration for the same carbon content and quench.
2. Ability to obtain the same surface hardness with a less drastic quench and in the case of some of alloys, a lower quenching temperature, thus giving less distortion.
3. Increasing toughness, as indicated by the higher values of yield point, elongation, and reduction of area.
4. Finer grain size, with the resulting higher impact toughness and increased wear resistance [22].

5.5 Gear Steel requirements

Some of the more important requirements for gear steels are there:

- Processing characteristics (hardenability and machinability).
- Response to heat treatment (normalizing, flame hardening induction hardening, carburizing and Nitriding).
- Resistance to tooth bending fatigue, because carburized steels for high performance gear applications are subjected to cyclic loading; this is one of the most important properties for measure the gear performance.
- Resistance to surface-contact (pitting) fatigue.
- Resistance to rolling contact fatigue.
- Resistance to wear [23].

5.6 Heat treatment required for gear steels

The gear designer should remember that, in most cases, the strength and hardness of the steel gear will depend primarily upon the skill and intelligence with which the steel has been heat treated, improper quenching or tempering at the wrong temperature will completely defeat the designer selection of the best steel for the application [28].

Heat treatment of steel gears is a complex process, and its scope lies from surface hardening to care treatment with proper control of both case and core microstructures. A well-controlled heat treatment produces the desirable surface and core properties for resistance to various failure modes. These failure modes include bending and contact (pitting) fatigues, and failures due to simple surface wear of gear teeth. Fig (5.2) shows the common gear failure. The type of heat treatment used significantly affects metallurgical properties of the gears and the subsequent failure modes of the gears [29].

Table 5-1 Chemical composition of gear steels [24], [25], [26] [27]

Steel Grade Standards			Chemical Compositions of Gear Steels %								
BS	**AISI**	**DIN**	**C**	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mo**	**Others**
080M15	1015	C15	0.13-0.18	0.30-0.60	0.04	0.05	--	--	--	--	--
120M19	1022	C22	0.17-0.23	0.70-1.00	0.04	0.05	--	--	--	--	--
080M30	1030	C30	0.28-0.34	0.60-0.90	0.04	0.05	--	--	--	--	--
080M40	1040	5C40	0.37-0.44	0.60-0.90	0.04	0.05	--	--	--	--	--
080M50	1050	C50	0.48-0.55	0.60-0.90	0.04	0.05	--	--	--	--	--
060A62	1060	C60	0.55-0.65	0.60-0.90	0.04	0.05	--	--	--	--	--
080A83	1080	--	0.74-0.88	0.60-0.90	0.04	0.05	--	--	--	--	--
060A96	1095	CK101	0.90-1.03	0.30-0.50	0.04	0.05	--	--	--	--	--
214M15	1118	--	0.14-0.20	1.30-1.60	0.04	0.08-0.13	--	--	--	--	--
216M44	1144	--	0.40-0.48	1.35-1.65	0.04	0.24-0.33					
150M36	1340	36Mn5	0.38-0.43	1.60-1.90	0.035	0.04	0.15-0.35	--	--	--	--
708A25	4130	25CrMo4	0.28-0.33	0.40-0.90	0.035	0.04	0.15-0.35	--	0.80-1.10	0.15-0.25	--
708M40	4140	42CrMo4	0.38-0.43	0.75-1.00	0.035	0.04	0.15-0.35	--	0.80-1.10	0.15-0.25	--
708M40	4150	50CrMo4	0.48-0.53	0.75-1.00	0.035	0.04	0.15-0.35	--	0.80-1.10	0.15-0.25	
815M17	4320	17CrNiMo6	0.17-0.22	0.45-0.65	0.035	0.04	0.15-0.35	1.65-2.00	0.40-0.60	0.20-0.30	--
817M40	4340	34CrNiMo6	0.38-0.43	0.60-0.80	0.035	0.04	0.15-0.35	1.65-2.00	0.70-0.90	0.20-0.30	--
665M20	4620	--	0.17-0.22	0.45-0.65	0.035	0.04	0.15-0.35	1.65-2.00	--	0.20-0.30	--
--	4820	--	0.18-0.23	0.50-0.70	0.035	0.04	0.15-0.35	3.25-3.75	--	0.20-0.30	--
530H32	5130	--	0.28-0.33	0.70-0.90	0.035	0.04	0.15-0.30	--	0.80-1.10	--	--
530M40	5140	41Cr4	0.38-0.43	0.70-0.90	0.035	0.04	0.15-0.30	--	0.70-0.90	--	--
--	5150	46Cr2	0.48-0.53	0.70-0.90	0.035	0.04	0.15-0.30	--	0.70-0.90	--	--
527H60	5160	--	0.56-0.64	0.75-1.00	0.035	0.04	0.15-0.30	--	0.70-0.90	--	--
735A51	6150	50CrV4	0.48-0.53	0.70-0.90	0.035	0.04	0.15-0.30	--	0.80-1.10	--	V 0.15 min.
805M20	8620	21Ni CrMo2	0.18-0.23	0.70-0.90	0.035	0.04	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	
945A40	8640	--	0.38-0.43	0.70-0.90	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25	--
708M40	8650	--	0.48-0.53	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25	--
805A60	8660	--	0.56-0.64	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25	--
--	8740	--	0.38-0.43	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.20-0.30	--
832H13	E9310	14NiCrMo13-4	0.08-0.13	0.45-0.65	0.025	0.025	0.15-0.30	3.00-3.50	1.00-1.40	0.08-0.15	--
722M24	--	32CrMo12	0.36-0.44	0.45-0.70	0.035	0.04	0.10-0.35	--	3.00-3.50	0.45-0.65	--
897M39	--	39CrMoV139	0.35-0.43	0.45-0.70	0.02	0.02	--	--	3.00-3.50	0.80-1.10	V 0.15-0.25
905M31	--	41CrAlMo7	0.35-0.43	0.40-0.65	0.02	0.02	--	--	1.40-1.80	0.15-0.25	Al 0.90-1.30
905M39	--	42CrAlMo7	0.38-0.45	0.50-0.80	0.03	0.03	0.20-0.40	--	1.50-1.30	0.25-0.40	Al 0.90-1.30

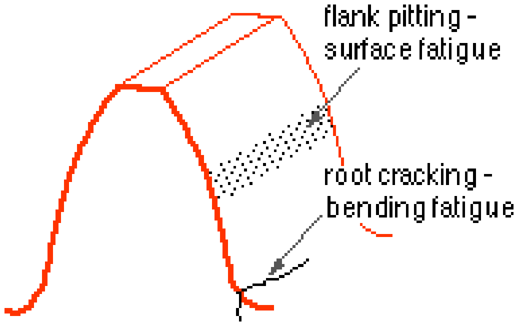


Figure 5-2 Common gears failure [28]

In addition to hardness and acceptable case/core microstructures, a gear design engineer expects gears to maintain pre-heat treat tooth geometry after heat treatment, if possible. This allows gears to be finished with such minor operations as honing or lapping at acceptable quality and cost. But unfortunately, the quality of gear geometry after heat treatment, carburizing in particular, deteriorates due to distortion depends on the material, heat treatment process, and equipment used. Although grinding can improve the geometry of gear teeth even with higher distortion, this increases manufacturing cost significantly. Furthermore, ground gears with high distortion may not perform satisfactory due to the fact that grinding may remove the required case and lower the surface hardness of teeth. Thus, for optimal gear performance and reasonable manufacturing cost, it is essential that gear designer and manufacturing engineers have a good understanding of the various heat treatment processes that are used primarily for industrial gears [29]. The major heat treatment processes of industrial gears are:

- Through-Hardening
- Case hardening :
    - Induction hardening.
    - Carburizing and hardening
    - Nitriding.

5.6.1 Through – Hardening gears

Through hardening is generally used for gears that do not require high surface hardness, typical gear tooth hardness after through hardening ranges from 32 to 48 HRC. Most steels used for through hardening have medium carbon content (0.3-0.6%) and relatively low alloy content (up to 3 %) . The purpose of allowing content is to increase hardenability, the higher the hardenability , the deeper is through hardening of gear teeth. Since the strength increases directly with hardness, high hardenability is essential for through hardening steels [29]. In through hardening, gears are first heated to a required temperature and then cooled either in the furnace or quenched in air, or liquid. The process may be used before or after the gear are cut. If applied before cutting the teeth, the hardness usually is governed and limited by the most feasible machining process. Since theses gear teeth are cut after heat treatment, no future finishing operation is needed. On the other hand, gears that are designed for hardness above the machining limit are first cut to semi - finish dimensions and then through hardened. In case of some minor heat treat distortion, a finishing operation such as lapping or grinding is very often used to improve the quality of these gears [22].

Four different methods of heat treatment are primarily used for hardness, these methods are annealing, normalizing, quenching, and tempering. Of the four commonly used through – hardening processes, the quench and temper method is used widely, particular when:

- The hardness and mechanical properties required for a given application cannot be achieved by any of the other three processes.
- It is necessary to develop mechanical properties (Core properties) in gears that will not be altered by any subsequent heat treatment such as Nitriding or induction hardening.

The hardness of through hardened gears generally is measured either on the gear tooth end face or rim section. This is the hardness that is used for gear rating purposes. Sometimes, achieving specified hardness on tooth end face may not necessarily assure the desired hardness at the roots of the teeth because of grade of steel, tooth size, and heat treat practice. If gear tooth root hardness is critical to a design, then it should be specified and measured on a sample (coupon) processed with the gears. However, needless increase of steels cost by selecting a higher grade of steel should be avoided [26]. Mechanical properties of gear steels as through hardening condition are shown in table (5.2).

Table 5-2 Mechanical properties of through hardened gear steels [4], [13], [24], [25], [26], [27], [30],[31]

Steel Grade Standards			heat treatment		Mechanical Properties as Through hardening condition							Cost $/Kg *10^-1 [1]
BS	AISI	DIN	Quenching Temp. ^{0}C& (medium)	Tempering temp.^{0}C	σ_{uts} Mpa	σ_y Mpa	Elong.%	Bending fatigue strength at 10^7 cycle Mpa	Surface Hardness HV	Impact value J	Machinability % [2]	
080M40	1040	C40	845 (Water)	205	898	663	16	397	505	7.0	70	0.8124
				315	893	648	18	395	395	16.0		
				540	780	593	23	360	271	18.0		
080M50	1050	C50	830 (Water)	205	1123	808	9	464	505	3.0	70	0.8124
				315	1090	793	13	455	436	3.0		
				540	860	655	23	385	290	5.0		
060A62	1060	C60	830 (Oil)	205	1103	780	13	458	319	18.0	70	0.8124
				315	1077	765	14	450	309	19.0		
				540	965	670	17	417	275	20.0		
080A83	1080	--	810 (Oil)	205	1310	980	12	517	383	14.0	70	0.8124
				315	1290	950	13	511	373	14.0		
				540	1133	808	16	467	319	11.0		
060A96	1095	CK101	800 (Oil)	205	1290	828	10	511	392	7.0	70	0.8124
				315	1263	813	10	504	373	7.0		
				540	1090	678	15	455	319	8.0		
216M44	1144	--	845 (Oil)	205	875	628	17	390	275	9.0	85	0.8002
				315	870	623	17	388	260	9.0		
				540	808	573	20	368	235	14.0		
150M36	1340	36Mn5	830 (Oil)	205	1808	1593	11	647	495	7.0	50	0.7995
				315	1588	1420	12	591	444	14.0		
				540	965	828	17	417	294	16.0		
708A25	4130	25CrMo4	855 (Water)	205	1610	1463	10	597	459	34.0	70	0.9123
				315	1498	1380	11	569	427	35.0		
				540	1033	910	17	438	314	27.0		
708M40	4150	50CrMo4	830 (Oil)	205	1930	1725	10	678	520	14.0	55	0.945
				315	1765	1590	10	636	485	15.0		
				540	1150	1105	15	488	365	24.0		
817M40	4340	34CrNiMo6	840 (Oil)	205	1823	1675	10	660	510	20.0	50	1.197
				315	1770	1588	10	637	476	27.0		
				540	1173	1078	13	478	365	46.0		
530M40	5140	41Cr4	845 (Oil)	205	1793	1640	9	644	481	14.0	65	0.8134
				315	1508	1448	10	589	441	7.0		
				540	1000	863	17	427	279	69.0		
--	5150	46Cr2	830 (Oil)	205	1945	1730	5	681	515	18.0	60	0.8408
				315	1738	1608	6	630	466	17.5		
				540	1123	1033	15	464	338	28.0		
527H60	5160	--	830 (Oil)	205	2220	1793	4	748	615	20.0	55	0.8565
				315	2000	1773	9	695	544	20.0		
				540	1165	1040	7	476	333	54.0		
735A51	6150	50CrV4	845 (Oil)	205	1930	1690	8	678	527	19.0	55	0.9269
				315	1725	1573	8	626	473	15.0		
				540	1158	1070	13	474	338	41.0		
708M40	8650	--	800 (Oil)	205	1938	1670	10	679	515	29.0	60	1.005
				315	1725	1550	10	626	481	34.0		
				540	1173	1053	15	478	333	41.0		
805A60	8660	--	800 (Oil)	205	1633	1550	13	603	451	22.0	55	1.02
				315	1310	1213	17	517	363	35.0		
				540	1068	950	20	448	310	46.0		
823M30	8740	30CrNiMo8	830 (Oil)	205	2000	1655	10	695	566	41.0	65	1.013
				315	1718	1550	11	625	486	45.0		
				540	1208	1138	15	488	358	47.0		

[1] Cost is included row steel price and heat treatment cost (5% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[2] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength

5.6.2 Case hardening

Case hardening processes is generally used to obtain mechanical properties for high performance. Induction hardening, carburizing and hardening, and Nitriding are the most recently used processes to produce the required properties.

The induction hardening generates heating and hardening only a small portion of the gear, so size change and distortion are relatively small, especially when comparing with carburized and hardening parts. but not all gears can hardened by induction because of size and shape and induction hardened gears has a small load carrying capacity , so Carburizing and hardened gears can used. Nitriding is used for some applications because of less distortion and no need for final finishing process, but involves long cycle process and is therefore very expensive [32].

5.6.2.1 Induction hardening

Induction hardening is a very common process of gear heat treatment. This process gives the surface region of a gear by induction coils. Induction hardening is able to heat up as steel's surface layers into austenite region. Higher hardness structures are obtained after quenching (Bainite or Martensite). The induction hardening process has capability to produce different case depths [32].

Accurate heating to the proper surface temperature is a critical step. Inductor design, heat input, and cycle time must be closely controlled, where under heating results in less than specified hardness and case depth. Overheating can result in cracking. Parts heated in an induction coil usually are quenched in an integral quench ring or in an agitated quench media [22]. Figure (5.3)

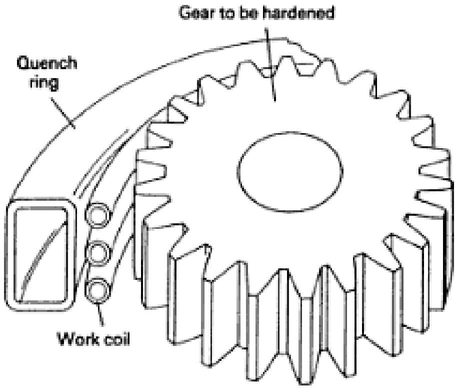


Figure 5-3 Quench ring and solenoid coil surrounding a gear to be induction hardened [29].

For large case depth, frequencies between 3 and 25 kHz are used. Table (5.3) shows approximate case depths that are normally achieved with induction hardened process.

Table 5-3 Current frequency vs. case depth for induction hardening [28]

Frequency ,kHz	Approximate case depth , mm (in)
3	3.81 (0.15)
10	1.52-2.0 (0.06-0.08)
500	0.51-1.0 (0.02-0.04)
1000	0.25-0.51 (0.01-0.02)

In induction – hardened tooth that requires high bending strength, it is necessary to get a reasonable hardness depth at the root fillet.

It’s quite difficult to obtain uniform case depth on a gear tooth with induction hardening. Typical case profile of induction hardened teeth is shown in figure (5.4). Furthermore it also is difficult to obtain a reasonable depth of hardness at the center of root fillet, which will lead a lower bending strength obtained compare with a carburized and hardened gear tooth [31]. Table (5.4) shows the mechanical properties of induction hardened gear steels.

Table 5-4 Mechanical properties of induction hardened gear steels. [4], [13], [24], [25], [26], [27], [30],[31]

Steel Grade Standards			[1]Induction Temp. ^0C	Mechanical Properties as Induction hardening							[2]Cost $/kg *$10^{-1}$
BS	AISI	DIN		σ_{uts} Mpa	σ_y Mpa	Elong %	Bending fatigue strength at 10^7 cycle Mpa	Surface hardness HV	Impact value J	[3]Machinability %	
080M30	1030	C30	870	460	345	37	381	490	69	65	0.779
080M40	1040	C40	860	515	350	35	397	505	45	60	0.795
080M50	1050	C50	850	635	365	24	464	610	18	50	0.812
060A62	1060	C60	850	625	370	22	458	615	11	50	0.826
080A83	1080	--	830	615	380	19	517	600	7	50	0.860
060A96	1095	CK101	810	450	285	34	565	588	5	50	0.705
708M40	4150	50CrMo4	875	731	380	20	678	588	24	50	0.945
530H32	5130	--	870	667	552	21	599	466	50	67	0.813
530M40	5140	41Cr4	880	573	293	29	644	600	41	60	0.841
735A51	6150	50CrV4	870	668	413	23	677	698	27	55	0.927
945A40	8640	--	860	945	931	9	660	600	7	60	0.988

[1] All steels are tempering at 200 ^0C

[2] Cost is included row steel price and heat treatment cost (7% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[3] Machinability % is measured as annealed condition and based on 100 % Machinability for AISI 1212 steel

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength

Furthermore, the maximum attainable surface hardness with induction hardening is about 55 HRC, which limits the durability of gears.

Another problem with an induction hardened gear is residual stress in the case/core interface. In this region, there are high residual stresses due to drastic differences of the case and core microstructures and the fact that the transition occurs in a very short distance [29]. Figure (5.5) shows the difference in case hardness gradients for induction hardened and carburized gear teeth.

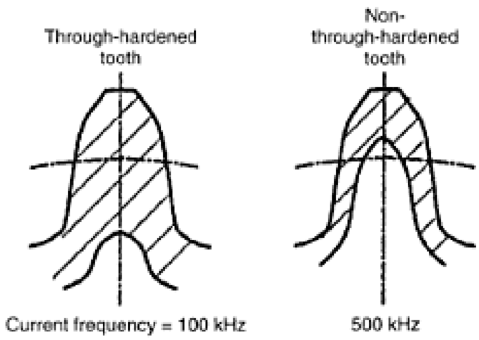


Figure 5-4 Case depth profile at different current frequency [29]

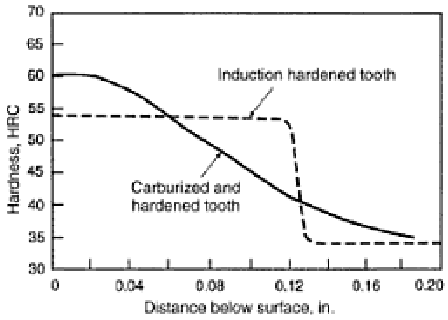


Figure 5-5 Comparison of hardness gradient-induction hardened and carburized gears [29]

5.6.2.2 Carburizing and hardening:

Carburizing and hardening process are most commonly used today for heat treating the gears. It is adequate for large and small gears; also can be used for high and low volume requirements. By selecting a proper steels and process can produce the highest allowable contact and bending stress rating [32]. The mechanical properties of the carburized gear steels are shown in table (5.5).

The primary objective of carburizing and hardening gears is to secure a hard case and a relatively soft but tough core. For this process, a low carbon steels (up to a maximum of approximately 0.30% carbon), either with or without alloying elements (nickel, chromium, manganese, molybdenum), normally are used. But coarser pitch, heavier sections and more sever service necessitate using higher hardenability, higher alloy steels. Many carburizing types are used to improve the gear surface such as gas, vacuum, and plasma carburizing [33].

Table 5-5 Mechanical properties of Carburized gear steels [4], [13], [24], [25], [26], [27], [30], [31]

Steel Grade Standards			[1]Mechanical Properties as Carburizing treatment							[2]Cost $/kg *$10^{-1}$
BS	AISI	DIN	σ_{uts} Mpa	σ_y Mpa	Elong. %	Bending fatigue strength at 10^7 cycle Mpa	Surface hardness HV	Impact value J	[3]Machinability %	
080M15	1015	C15	425	328	15	294	228	54	60	0.795
120M19	1022	C22	483	358	26	265	276	46	60	0.761
214M15	1118	--	478	320	34	270	300	88	80	0.795
815M17	4320	17CrNiMo6	793	465	21	360	440	31	70	1.152
665M20	4620	--	575	368	29	290	269	30	65	1.135
--	4820	--	753	485	22	350	425	45	50	1.365
805M20	8620	21Ni CrMo2	860	565	23	400	388	15	60	0.972
832H13	E9310	14NiCrMo13-4	908	570	19	450	365	38	40	1.289

[1] Gas Carburizing at 915 ^{0}C, for 8 hours, 775 ^{0}C reheat, Water quench, 175 ^{0}C temper.

[2] Cost is included row steel price and heat treatment cost (10% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[3] Machinability % is measured as annealed condition and based on 100 % Machinability for AISI 1212 steel

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength

After case carburizing the gear teeth will have high carbon content at the surface and graduating into the low carbon toward the core. Figure (5.6) shows the gear carburized layer.

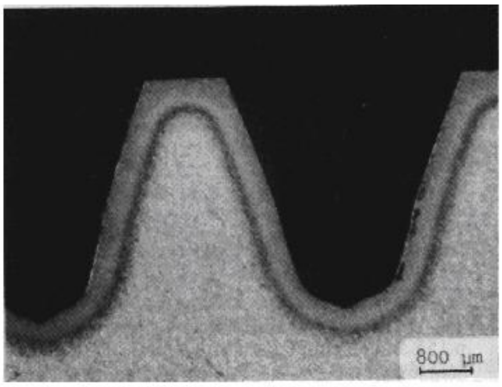


Figure 5-6 Carburized layer of gear (low carbon steel) [32].

Some times to prevent through hardening of the tooth tip, carbon penetration through tip of tooth needs to be controlled. This accomplished by plating or spraying the outside diameter of gear before cutting the teeth with some material that prevents the passage of the carburizing agent. However, the most widely used method is copper plating.

Distortion and the size change are the most problem of carburized and hardened gears during hardening process. This is very design-dependent. For non-symmetrical cross sectional gears distortion will be more than symmetrical cross sectional. Fixturing the gear during carburizing and hardening processes is very important to minimize the creep-induced distortion, and to obtain uniform hardened case the direction of the gear must be considered during quenching process. Furthermore, using a hot oil (50 -80 C^0) for quenching, marquenching, and high pressure gas quenching are used to minimize the size change and distortion, but since they are slower quenches, it is often necessary to use a higher hardenability steels than necessary with conventional oil quenching [29].

The depth of the carburized case is varying depending on the diametral pitch and service requirements of the gear. Thick or coarser pitches and more sever conditions require deeper cases [31].

Figure (5.7) shows the effective case depth to be used for a given diametral pitch.

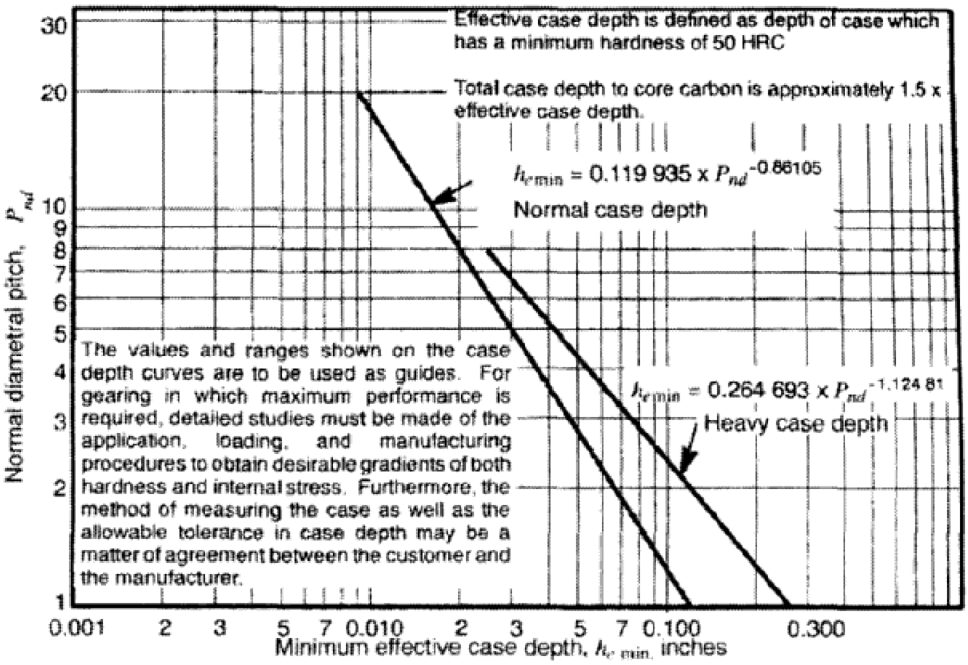


Figure 5-7 Carburized case depth requirements [32].

5.6.3 Nitriding

Nitriding is used for high performance gearing due to a hard surface with excellent wear properties, improved corrosion properties and very good high cycle fatigue properties. Nitriding is usually performed in a low temperature (490 to 520 ^{0}C) and quenching is not necessary.

Nitrided gears have less size changes and distortion because of there is no structure change, and no need to finishing process normally, however, is relatively long process (40 to 60 hrs) so, it is highly cost process. Three different types of medium carbon alloy steels are used for nitrided gears, depending on the service requirements [32]. Table (5.6) shows the mechanical properties of nitrided gear steels.

Table 5-6 Mechanical properties of Nitrided gear steels [4], [13], [24], [25], [26], [27], [30], [31]

Steel Grade Standards			Core treatment		[1]Mechanical Properties as Nitriding treatment							[2]Cost $/kg $*10^{-1}$
BS	AISI	DIN	Hardening Temp. ^0C oil quench	Tempering Temp. ^0C	σ_{uts} Mpa	σ_y Mpa	Elong. %	Bending fatigue strength at 10^7 cycle Mpa	Surface hardness HV	Impact value J	[3]Machinability %	
708M40	4140	42CrMo4	860	500	1080	765	11	497	640	54	60	1.007
722M24	--	32CrMo12	900	570	1080	785	11	497	800	97	60	1.109
817M40	4340	34CrNiMo6	840	550	1180	885	10	543	580	54	60	1.317
897M39	--	--	920	600	850	660	13	391	950	123	55	1.333
905M31	--	--	920	570	855	590	14	393	1150	90	50	1.410
905M39	--	41CrAlMo7	920	600	1030	735	17	474	900	92	50	1.450

[1] Gas Nitriding at 520 ^0C, for 48 hours.

[2] Cost is included row steel price and heat treatment cost (10% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[3] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength

For good Nitriding response core hardening and tempering is employed to produce both the desired strength. Figure (5.8) shows the total nitrided case depth required for different hardness processes [32].

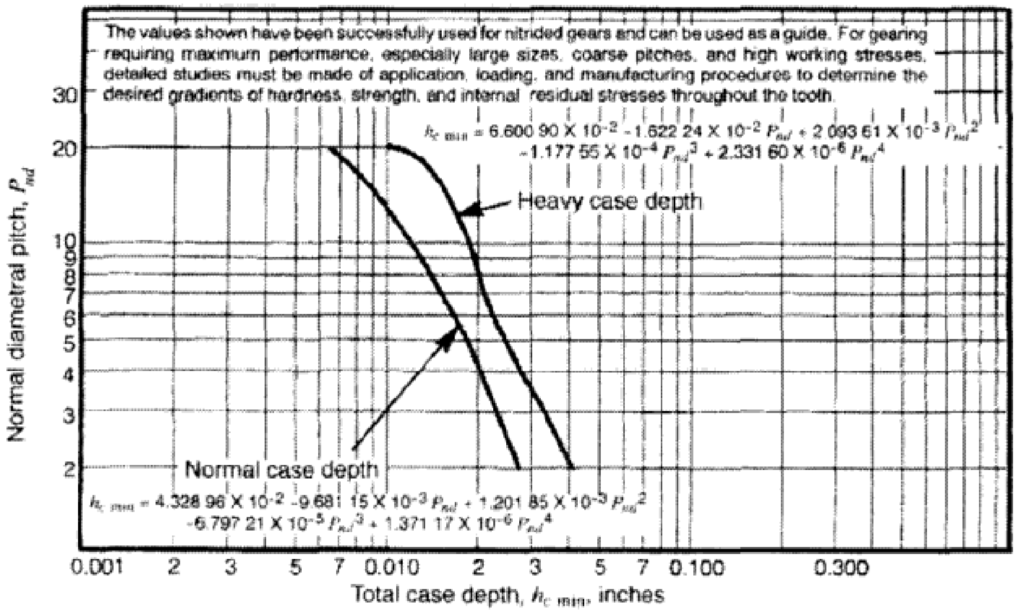


Figure 5-8Nitrided case depth requirements [32]

5.7 Selection of gear steels by using weighted property method

The method of multifactor objective function described in chapter 4 (sec.4.3.4), where each steel property is assigned a certain weight depending on its importance to required design requirements. A performance index is obtained by multiplying the property scaled value by weighting factor.

As a first step in the weighted property method is to scale the properties given in table (5.2, 5.4, 5.5, & 5.6), the higher mechanical properties are more desirable and highest values are considered as 100. Other values are rated in proportion according to Eq. (4.1). On the other hand, while lower value of cost is more desirable so, lowest value will consider as 100 and other values in table rated in proportion percentage according to Eq. (4.2). The scaled value of gear steels are given in table (5.7).

For gear applications five important properties or requirement are considered to evaluate the selection process, wear resistance (surface hardness) bending fatigue strength, toughness (impact strength), machinability, and cost.

Table 5-7 Scaled property value of gear steels properties

Steel Grade Standards			Condition	Scaled values of Gear steels				
				Scaled property				
BS	AISI	DIN		Surface Hardness	Toughness	Bending Fatigue Strength	Machinability	Cost
080M15	1015	C15	carburized	19.83	43.9	42.3	70.59	95.83
120M19	1022	C22	carburized	24	37.4	38.13	70.59	100
214M15	1118	--	carburized	26.09	71.54	38.85	94.12	95.83
665M20	4620	--	carburized	23.39	24.39	41.73	76.47	67.08
815M17	4320	17CrNiMo6	carburized	38.26	25.2	51.8	82.35	66.09
--	4820	--	carburized	36.96	36.59	50.36	58.82	55.78
805M20	8620	21Ni CrMo2	carburized	33.74	12.2	57.55	70.59	78.34
832H13	E9310	14NiCrMo13-4	carburized	31.74	30.89	64.75	47.06	59.07
080M30	1030	C30	Induction hardened	42.61	56.42	54.82	76.47	97.74
080M40	1040	C40	Induction hardened	43.91	36.59	57.12	70.59	95.83
080M50	1050	C50	Induction hardened	53.04	14.63	66.76	58.82	93.72
060A62	1060	C60	Induction hardened	53.48	8.94	65.9	58.82	92.16
080A83	1080	--	Induction hardened	52.17	5.69	74.39	58.82	88.13
060A96	1095	CK101	Induction hardened	51.13	4.07	81.29	58.82	89.58
708M40	4150	50CrMo4	Induction hardened	51.13	19.51	97.55	58.82	80.57
530H32	5130	--	Induction hardened	40.52	40.65	86.19	78.82	93.61
530M40	5140	41Cr4	Induction hardened	52.17	33.33	92.66	70.59	90.56
735A51	6150	50CrV4	Induction hardened	60.7	21.95	97.41	64.71	82.14
945A40	8640	--	Induction hardened	52.17	5.69	94.96	70.59	77.06
080M40	1040	C40	H & T at 205	43.91	5.69	57.12	82.35	93.72
080M40	1040	C40	H & T at 315	34.35	13.01	56.83	82.35	93.72
080M40	1040	C40	H & T at 540	23.57	14.63	51.8	82.35	93.72
080M50	1050	C50	H & T at 205	43.91	2.44	66.76	82.35	93.72
080M50	1050	C50	H & T at 315	37.91	2.44	65.47	82.35	93.72
080M50	1050	C50	H & T at 540	25.22	4.07	55.4	82.35	93.72
060A62	1060	C60	H & T at 205	27.74	14.63	65.9	127.27	93.72
060A62	1060	C60	H & T at 315	26.87	15.45	64.75	82.35	93.72
060A62	1060	C60	H & T at 540	23.91	16.26	60	82.35	93.72
080A83	1080	--	H & T at 205	33.3	11.38	74.39	82.35	93.72
080A83	1080	--	H & T at 315	32.43	11.38	73.53	82.35	93.72
080A83	1080	--	H & T at 540	27.74	8.94	67.19	82.35	93.72
060A96	1095	CK101	H & T at 205	34.09	5.69	73.53	82.35	93.72
060A96	1095	CK101	H & T at 315	32.43	5.69	72.52	82.35	93.72
060A96	1095	CK101	H & T at 540	27.74	6.5	65.47	82.35	93.72
216M44	1144	--	H & T at 205	23.91	7.32	56.12	100	95.15
216M44	1144	--	H & T at 315	22.61	7.32	55.83	100	95.15
216M44	1144	--	H & T at 540	20.43	11.38	52.95	100	95.15
150M36	1340	36Mn5	H & T at 205	43.04	5.69	93.09	58.82	95.23
150M36	1340	36Mn5	H & T at 315	38.61	11.38	85.04	58.82	95.23
150M36	1340	36Mn5	H & T at 540	25.57	13.01	60	58.82	95.23
708A25	4130	25CrMo4	H & T at 205	39.91	27.64	85.9	82.35	83.46
708A25	4130	25CrMo4	H & T at 315	37.13	28.46	81.87	82.35	83.46
708A25	4130	25CrMo4	H & T at 540	27.3	21.95	63.02	82.35	83.46
708M40	4150	50CrMo4	H & T at 205	45.22	11.38	97.55	64.71	80.57
708M40	4150	50CrMo4	H & T at 315	42.17	12.2	91.51	64.71	80.57
708M40	4150	50CrMo4	H & T at 540	31.74	19.51	70.22	64.71	80.57
817M40	4340	34CrNiMo6	H & T at 205	44.35	16.26	94.96	58.82	63.61
817M40	4340	34CrNiMo6	H & T at 315	41.39	21.95	91.65	58.82	63.61
817M40	4340	34CrNiMo6	H & T at 540	31.74	37.4	68.78	58.82	63.61
530M40	5140	41Cr4	H & T at 205	41.83	11.38	92.66	76.47	93.61
530M40	5140	41Cr4	H & T at 315	38.35	13.01	84.75	76.47	93.61
530M40	5140	41Cr4	H & T at 540	24.26	44.72	61.44	76.47	93.61
--	5150	46Cr2	H & T at 205	44.78	14.63	97.99	70.59	90.56
--	5150	46Cr2	H & T at 315	40.52	14.23	90.65	70.59	90.56
--	5150	46Cr2	H & T at 540	29.39	22.76	66.76	70.59	90.56
527H60	5160	--	H & T at 205	53.48	16.26	107.63	64.71	88.9
527H60	5160	--	H & T at 315	47.3	16.26	100	64.71	88.9
527H60	5160	--	H & T at 540	28.96	43.9	68.49	64.71	88.9
735A51	6150	50CrV4	H & T at 205	45.83	15.45	97.55	64.71	82.14
735A51	6150	50CrV4	H & T at 315	41.13	12.2	90.07	64.71	82.14
735A51	6150	50CrV4	H & T at 540	29.39	33.33	68.2	64.71	82.14
708M40	8650	--	H & T at 205	44.78	23.58	97.7	70.59	75.76
708M40	8650	--	H & T at 315	41.83	27.64	90.07	70.59	75.76
708M40	8650	--	H & T at 540	28.96	33.33	68.78	70.59	75.76
805A60	8660	--	H & T at 205	39.22	17.89	86.76	64.71	74.65
805A60	8660	--	H & T at 315	31.57	28.46	74.39	64.71	74.65
805A60	8660	--	H & T at 540	26.96	37.4	64.46	64.71	74.65
823M30	8740	30CrNiMo8	H & T at 205	49.22	33.33	100	76.47	75.16
823M30	8740	30CrNiMo8	H & T at 315	42.26	36.59	89.93	76.47	75.16
823M30	8740	30CrNiMo8	H & T at 540	31.13	38.21	70.22	76.47	75.16
708M40	4140 N	42CrMo4	Nitrided	55.65	43.9	71.51	70.59	75.61
722M24	--	32CrMo12	Nitrided	69.57	78.86	71.51	70.59	68.66
817M40	4340	34CrNiMo6	Nitrided	50.43	43.9	78.13	70.59	57.81
897M39	--	--	Nitrided	82.61	100	56.26	64.71	57.12
905M31	--	--	Nitrided	100	73.17	56.55	58.82	54
905M39	--	41CrAlMo7	Nitrided	78.26	74.8	68.2	58.82	52.51
	Maximum scaled property of Gear Steels							

5.7.1 Selection of high fatigue strength gear steels

5.7.1.1 Relative importance of gear requirements (Weighting factor):

When many steels properties are used to specify gears performance, it may be difficult to find out the weighting factors (α). One way to do so is to use a digital logic approach. Each property is listed and is compared in every combination, taken two at a time as described in chapter4 (sec. 4.3.4). With five properties required for gears design, the total number of possible decisions is ***N (N-1)/2 = 5(5-1)/4= 10***. The different decisions are given in table (5.8).

Table 5-8 Weighting factors for fatigue strength gear steels.

Determination of relative importance of required properties for Fatigue Strength gear steels by using the digital logic method													
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Fatigue strength	1	1	1	1							4	0.400
Surface hardness	0				1	1	1				3	0.300
Toughness		0			0			1	0		1	0.100
Machinability			0			0		0		1	1	0.100
Cost				0			0		1	0	1	0.100
											10	**1.000**

5.7.1.2 Performance index (γ) for fatigue strength gear steels

The final step to select appropriate steel for fatigue strength gears application is to find out the performance index of gear steels for each specified gear requirement by using Eq. (4.3). The performance index calculation shows that **(*BS 527H60, AISI 5160*)** steel in hardened and tempered at 205 ^{0}C conditions is the optimum steel can be used for high fatigue strength gear. The ranking list (highest 5 ranked steels are red coloured) of high fatigue gear steels is indicated in table (5.9).

Table 5-9 Performance index & ranking of high fatigue gear steels

Performance index & Ranking for Fatigue Strength gear steels										
Steel Grade Standards			Condition	Surface hardness	Toughness	Fatigue strength	Machinability	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
080M15	1015	C15	Carburized	5.9	4.4	16.9	7.1	9.6	43.9	
120M19	1022	C22	Carburized	7.2	3.7	15.3	7.1	10.0	43.3	
214M15	1118	--	Carburized	7.8	7.2	15.5	9.4	9.6	49.5	
665M20	4620	--	Carburized	7.0	2.4	16.7	7.6	6.7	40.5	
815M17	4320	17CrNiMo6	Carburized	11.5	2.5	20.7	8.2	6.6	49.6	
--	4820	--	Carburized	11.1	3.7	20.1	0.0	5.6	40.5	
805M20	8620	21Ni CrMo2	Carburized	10.1	1.2	23.0	7.1	7.8	49.3	
832H13	E9310	14NiCrMo13-4	Carburized	9.5	3.1	25.9	4.7	5.9	49.1	
080M30	1030	C30	Induction hardened	12.8	5.6	21.9	7.6	9.8	57.8	
080M40	1040	C40	Induction hardened	13.2	3.7	22.8	7.1	9.6	56.3	
080M50	1050	C50	Induction hardened	15.9	1.5	26.7	5.9	9.4	59.3	
060A62	1060	C60	Induction hardened	16.0	0.9	26.4	5.9	9.2	58.4	
080A83	1080	--	Induction hardened	15.7	0.6	29.8	5.9	8.8	60.7	
060A96	1095	CK101	Induction hardened	15.3	0.4	32.5	5.9	9.0	63.1	
708M40	4150	50CrMo4	Induction hardened	15.3	2.0	39.0	5.9	8.1	70.3	**7**
530H32	5130	--	Induction hardened	12.2	4.1	34.5	7.9	9.4	67.9	
530M40	5140	41Cr4	Induction hardened	15.7	3.3	37.1	7.1	9.1	72.2	**4**
735A51	6150	50CrV4	Induction hardened	18.2	2.2	39.0	6.5	8.2	74.1	**2**
945A40	8640	--	Induction hardened	15.7	0.6	38.0	7.1	7.7	69.0	
080M40	1040	C40	H & T at 205	13.2	0.6	22.8	8.2	9.4	54.2	
080M40	1040	C40	H & T at 315	10.3	1.3	22.7	8.2	9.4	51.9	
080M40	1040	C40	H & T at 540	7.1	1.5	20.7	8.2	9.4	46.9	
080M50	1050	C50	H & T at 205	13.2	0.2	26.7	8.2	9.4	57.7	
080M50	1050	C50	H & T at 315	11.4	0.2	26.2	8.2	9.4	55.4	
080M50	1050	C50	H & T at 540	7.6	0.4	22.2	8.2	9.4	47.7	
060A62	1060	C60	H & T at 205	8.3	1.5	26.4	12.7	9.4	58.2	
060A62	1060	C60	H & T at 315	8.1	1.5	25.9	8.2	9.4	57.6	
060A62	1060	C60	H & T at 540	7.2	1.6	24.0	8.2	9.4	54.9	
080A83	1080	--	H & T at 205	10.0	1.1	29.8	8.2	9.4	58.5	
080A83	1080	--	H & T at 315	9.7	1.1	29.4	8.2	9.4	57.9	
080A83	1080	--	H & T at 540	8.3	1.3	26.9	8.2	9.4	54.1	
060A96	1095	CK101	H & T at 205	10.2	0.6	29.4	8.2	9.4	57.8	
060A96	1095	CK101	H & T at 315	9.7	0.6	29.0	8.2	9.4	56.9	
060A96	1095	CK101	H & T at 540	8.3	0.7	26.2	8.2	9.4	52.8	
216M44	1144	--	H & T at 205	7.2	0.7	22.4	10.0	9.5	49.9	
216M44	1144	--	H & T at 315	6.8	0.7	22.3	10.0	9.5	49.4	
216M44	1144	--	H & T at 540	6.1	1.1	21.2	10.0	9.5	48.0	
150M36	1340	36Mn5	H & T at 205	12.9	0.6	37.2	5.9	9.5	66.1	
150M36	1340	36Mn5	H & T at 315	11.6	1.1	34.0	5.9	9.5	62.1	
150M36	1340	36Mn5	H & T at 540	7.7	1.3	24.0	5.9	9.5	48.4	
708A25	4130	25CrMo4	H & T at 205	12.0	2.8	34.4	8.2	8.3	65.7	
708A25	4130	25CrMo4	H & T at 315	11.1	2.8	32.7	8.2	8.3	63.3	
708A25	4130	25CrMo4	H & T at 540	8.2	2.2	25.2	8.2	8.3	52.2	
708M40	4150	50CrMo4	H & T at 205	13.6	1.1	39.0	6.5	8.1	68.3	
708M40	4150	50CrMo4	H & T at 315	12.7	1.2	36.6	6.5	8.1	65.0	
708M40	4150	50CrMo4	H & T at 540	9.5	2.0	28.1	6.5	8.1	54.1	
817M40	4340	34CrNiMo6	H & T at 205	13.3	1.6	38.0	5.9	6.4	65.2	
817M40	4340	34CrNiMo6	H & T at 315	12.4	2.2	36.7	5.9	6.4	63.5	
817M40	4340	34CrNiMo6	H & T at 540	9.5	3.7	27.5	5.9	6.4	53.0	
530M40	5140	41Cr4	H & T at 205	12.5	1.1	37.1	7.6	9.4	67.8	
530M40	5140	41Cr4	H & T at 315	11.5	1.3	33.9	7.6	9.4	63.7	
530M40	5140	41Cr4	H & T at 540	7.3	4.5	24.6	7.6	9.4	53.3	
--	5150	46Cr2	H & T at 205	13.4	1.5	39.2	7.1	9.1	70.2	**8**
--	5150	46Cr2	H & T at 315	12.2	1.4	36.3	7.1	9.1	66.0	
--	5150	46Cr2	H & T at 540	8.8	2.3	26.7	7.1	9.1	53.9	
527H60	**5160**	**--**	**H & T at 205**	**16.0**	**1.6**	**43.1**	**6.5**	**8.9**	**76.1**	**1**
527H60	5160	--	H & T at 315	14.2	1.6	40.0	6.5	8.9	71.2	**6**
527H60	5160	--	H & T at 540	8.7	4.4	27.4	6.5	8.9	55.8	
735A51	6150	50CrV4	H & T at 205	13.7	1.5	39.0	6.5	8.2	69.0	
735A51	6150	50CrV4	H & T at 315	12.3	1.2	36.0	6.5	8.2	64.3	
735A51	6150	50CrV4	H & T at 540	8.8	3.3	27.3	6.5	8.2	54.1	
708M40	8650	--	H & T at 205	13.4	2.4	39.1	7.1	7.6	69.5	**9**
708M40	8650	--	H & T at 315	12.5	2.8	36.0	7.1	7.6	66.0	
708M40	8650	--	H & T at 540	8.7	3.3	27.5	7.1	7.6	54.2	
805A60	8660	--	H & T at 205	11.8	1.8	34.7	6.5	7.5	62.2	
805A60	8660	--	H & T at 315	9.5	2.8	29.8	6.5	7.5	56.0	
805A60	8660	--	H & T at 540	8.1	3.7	25.8	6.5	7.5	51.5	
823M30	8740	30CrNiMo8	H & T at 205	14.8	3.3	40.0	7.6	7.5	73.3	**3**
823M30	8740	30CrNiMo8	H & T at 315	12.7	3.7	36.0	7.6	7.5	67.5	**15**
823M30	8740	30CrNiMo8	H & T at 540	9.3	3.8	28.1	7.6	7.5	56.4	
708M40	4140 N	42CrMo4	Nitrided	16.7	4.4	28.6	7.1	7.6	64.3	
722M24	--	32CrMo12	Nitrided	20.9	7.9	28.6	7.1	6.9	71.3	**5**
817M40	4340	34CrNiMo6	Nitrided	15.1	4.4	31.3	7.1	5.8	63.6	
897M39	--	--	Nitrided	24.8	10.0	22.5	6.5	5.7	69.5	**9**
905M31	--	--	Nitrided	30.0	7.3	22.6	5.9	5.4	71.2	**6**
905M39	--	41CrAlMo7	Nitrided	23.5	7.5	27.3	5.9	5.3	69.4	**10**

5.7.2 Selection of high toughness gear steels

5.7.2.1 Relative importance of gear requirements (Weighting factor)

Toughness will be considered as the most important property for gear requirements as shown in table (5.10).

Table 5-10 Weighting factors for high toughness gear steels.

Determination of relative importance of required properties for high toughness gear steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Toughness	1	1	1	1							4	0.400
Fatigue strength	0				1	1	1				3	0.300
Surface hardness		0			0			1	0		1	0.100
Machinability			0			0		0		1	1	0.100
Cost				0			0		1	0	1	0.100
											10	1.000

5.7.2.2 Performance index (γ) for high toughness gear steels

Performance index calculations are shown the best steel can be used for high toughness gear is ***(BS 905M31)*** steel in nitrided condition.

The ranking list for high toughness gear steels (highest 5 ranked steels are red colured) is shown in table (5.11)

Table 5-11 performance index & ranking of high toughness gear steels

Performance index & Ranking for Fatigue Strength gear steels										
Steel Grade Standards			Condition	Surface hardness	Toughness	Fatigue strength	Machinability	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
080M15	1015	C15	Carburized	2.0	17.6	12.7	7.1	9.6	48.9	
120M19	1022	C22	Carburized	2.4	15.0	11.4	7.1	10.0	45.9	
214M15	1118	--	Carburized	2.6	28.6	11.7	9.4	9.6	61.9	
665M20	4620	--	Carburized	2.3	9.8	12.5	7.6	6.7	39.0	
815M17	4320	17CrNiMo6	Carburized	3.8	10.1	15.5	8.2	6.6	44.3	
--	4820	--	Carburized	3.7	14.6	15.1	0.0	5.6	39.0	
805M20	8620	21Ni CrMo2	Carburized	3.4	4.9	17.3	7.1	7.8	40.4	
832H13	E9310	14NiCrMo13-4	Carburized	3.2	12.4	19.4	4.7	5.9	45.6	
080M30	1030	C30	Induction hardened	4.3	22.6	16.4	7.6	9.8	60.7	
080M40	1040	C40	Induction hardened	4.4	14.6	17.1	7.1	9.6	52.8	
080M50	1050	C50	Induction hardened	5.3	5.9	20.0	5.9	9.4	46.4	
060A62	1060	C60	Induction hardened	5.3	3.6	19.8	5.9	9.2	43.8	
080A83	1080	--	Induction hardened	5.2	2.3	22.3	5.9	8.8	44.5	
060A96	1095	CK101	Induction hardened	5.1	1.6	24.4	5.9	9.0	46.0	
708M40	4150	50CrMo4	Induction hardened	5.1	7.8	29.3	5.9	8.1	56.1	
530H32	5130	--	Induction hardened	4.1	16.3	25.9	7.9	9.4	63.4	
530M40	5140	41Cr4	Induction hardened	5.2	13.3	27.8	7.1	9.1	62.5	
735A51	6150	50CrV4	Induction hardened	6.1	8.8	29.2	6.5	8.2	58.8	
945A40	8640	--	Induction hardened	5.2	2.3	28.5	7.1	7.7	50.7	
080M40	1040	C40	H & T at 205	4.4	2.3	17.1	8.2	9.4	41.4	
080M40	1040	C40	H & T at 315	3.4	5.2	17.1	8.2	9.4	43.3	
080M40	1040	C40	H & T at 540	2.4	5.9	15.5	8.2	9.4	41.4	
080M50	1050	C50	H & T at 205	4.4	1.0	20.0	8.2	9.4	43.0	
080M50	1050	C50	H & T at 315	3.8	1.0	19.6	8.2	9.4	42.0	
080M50	1050	C50	H & T at 540	2.5	1.6	16.6	8.2	9.4	38.4	
060A62	1060	C60	H & T at 205	2.8	5.9	19.8	12.7	9.4	50.5	
060A62	1060	C60	H & T at 315	2.7	6.2	19.4	8.2	9.4	50.4	
060A62	1060	C60	H & T at 540	2.4	6.5	18.0	8.2	9.4	49.0	
080A83	1080	--	H & T at 205	3.3	4.6	22.3	8.2	9.4	47.8	
080A83	1080	--	H & T at 315	3.2	4.6	22.1	8.2	9.4	47.5	
080A83	1080	--	H & T at 540	2.8	5.2	20.2	8.2	9.4	45.7	
060A96	1095	CK101	H & T at 205	3.4	2.3	22.1	8.2	9.4	45.4	
060A96	1095	CK101	H & T at 315	3.2	2.3	21.8	8.2	9.4	44.9	
060A96	1095	CK101	H & T at 540	2.8	2.6	19.6	8.2	9.4	42.6	
216M44	1144	--	H & T at 205	2.4	2.9	16.8	10.0	9.5	41.7	
216M44	1144	--	H & T at 315	2.3	2.9	16.7	10.0	9.5	41.5	
216M44	1144	--	H & T at 540	2.0	4.6	15.9	10.0	9.5	42.0	
150M36	1340	36Mn5	H & T at 205	4.3	2.3	27.9	5.9	9.5	49.9	
150M36	1340	36Mn5	H & T at 315	3.9	4.6	25.5	5.9	9.5	49.3	
150M36	1340	36Mn5	H & T at 540	2.6	5.2	18.0	5.9	9.5	41.2	
708A25	4130	25CrMo4	H & T at 205	4.0	11.1	25.8	8.2	8.3	57.4	
708A25	4130	25CrMo4	H & T at 315	3.7	11.4	24.6	8.2	8.3	56.2	
708A25	4130	25CrMo4	H & T at 540	2.7	8.8	18.9	8.2	8.3	47.0	
708M40	4150	50CrMo4	H & T at 205	4.5	4.6	29.3	6.5	8.1	52.9	
708M40	4150	50CrMo4	H & T at 315	4.2	4.9	27.5	6.5	8.1	51.1	
708M40	4150	50CrMo4	H & T at 540	3.2	7.8	21.1	6.5	8.1	46.6	
817M40	4340	34CrNiMo6	H & T at 205	4.4	6.5	28.5	5.9	6.4	51.7	
817M40	4340	34CrNiMo6	H & T at 315	4.1	8.8	27.5	5.9	6.4	52.7	
817M40	4340	34CrNiMo6	H & T at 540	3.2	15.0	20.6	5.9	6.4	51.0	
530M40	5140	41Cr4	H & T at 205	4.2	4.6	27.8	7.6	9.4	53.5	
530M40	5140	41Cr4	H & T at 315	3.8	5.2	25.4	7.6	9.4	51.5	
530M40	5140	41Cr4	H & T at 540	2.4	17.9	18.4	7.6	9.4	55.8	
--	5150	46Cr2	H & T at 205	4.5	5.9	29.4	7.1	9.1	55.8	
--	5150	46Cr2	H & T at 315	4.1	5.7	27.2	7.1	9.1	53.1	
--	5150	46Cr2	H & T at 540	2.9	9.1	20.0	7.1	9.1	48.2	
527H60	5160	--	H & T at 205	5.3	6.5	32.3	6.5	8.9	59.5	
527H60	5160	--	H & T at 315	4.7	6.5	30.0	6.5	8.9	56.6	
527H60	5160	--	H & T at 540	2.9	17.6	20.5	6.5	8.9	56.4	
735A51	6150	50CrV4	H & T at 205	4.6	6.2	29.3	6.5	8.2	54.7	
735A51	6150	50CrV4	H & T at 315	4.1	4.9	27.0	6.5	8.2	50.7	
735A51	6150	50CrV4	H & T at 540	2.9	13.3	20.5	6.5	8.2	51.4	
708M40	8650	--	H & T at 205	4.5	9.4	29.3	7.1	7.6	57.9	
708M40	8650	--	H & T at 315	4.2	11.1	27.0	7.1	7.6	56.9	
708M40	8650	--	H & T at 540	2.9	13.3	20.6	7.1	7.6	51.5	
805A60	8660	--	H & T at 205	3.9	7.2	26.0	6.5	7.5	51.0	
805A60	8660	--	H & T at 315	3.2	11.4	22.3	6.5	7.5	50.8	
805A60	8660	--	H & T at 540	2.7	15.0	19.3	6.5	7.5	50.9	
823M30	8740	30CrNiMo8	H & T at 205	4.9	13.3	30.0	7.6	7.5	63.4	5
823M30	8740	30CrNiMo8	H & T at 315	4.2	14.6	27.0	7.6	7.5	61.0	
823M30	8740	30CrNiMo8	H & T at 540	3.1	15.3	21.1	7.6	7.5	54.6	
708M40	4140 N	42CrMo4	Nitrided	5.6	17.6	21.5	7.1	7.6	59.2	
722M24	--	32CrMo12	Nitrided	7.0	31.5	21.5	7.1	6.9	73.9	2
817M40	4340	34CrNiMo6	Nitrided	5.0	17.6	23.4	7.1	5.8	58.9	
897M39	**--**	**--**	**Nitrided**	**8.3**	**40.0**	**16.9**	**6.5**	**5.7**	**77.3**	**1**
905M31	--	--	Nitrided	10.0	29.3	17.0	5.9	5.4	67.5	4
905M39	--	41CrAlMo7	Nitrided	7.8	29.9	20.5	5.9	5.3	69.3	3

5.7.3 Selection of high wear resistance gear steels

5.7.3.1 Relative importance of gear requirements (Weighting factor)

Surface hardness will be considered as the most important property for gear requirements as shown in table (5.12).

Table 5-12 weighting factors for wear resistance gear steels.

Determination of relative importance of required properties for Wear Resistance gear steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Surface hardness	1	1	1	1							4	0.400
Fatigue strength	0				1			1	1		3	0.300
Toughness		0			0	1	0				1	0.100
Machinability			0			0		0		1	1	0.100
Cost				0			1		0	0	1	0.100
											10	**1.000**

5.7.3.2 Performance index (γ) for wear resistance gear steels

Performance index calculations are shown the best steel can be used for wear resistance gear steels is ***(BS 905M31)*** steel in nitrided condition.

The ranking list for wear resistance gear steel (highest 5 ranked steels are red colured) is shown in table (5.13).

Table 5-13 performance index & ranking of wear resistance gear steels

Performance index & Ranking for Wear Resistance gear steels										
Steel Grade Standards			Condition	Surface hardness	Toughness	Fatigue strength	Machinability	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
080M15	1015	C15	Carburized	7.9	4.4	12.7	7.1	9.6	41.7	
120M19	1022	C22	Carburized	9.6	3.7	11.4	7.1	10.0	41.8	
214M15	1118	--	Carburized	10.4	7.2	11.7	9.4	9.6	48.2	
665M20	4620	--	Carburized	9.4	2.4	12.5	7.6	6.7	38.7	
815M17	4320	17CrNiMo6	Carburized	15.3	2.5	15.5	8.2	6.6	48.2	
--	4820	--	Carburized	14.8	3.7	15.1	0.0	5.6	39.1	
805M20	8620	21Ni CrMo2	Carburized	13.5	1.2	17.3	7.1	7.8	46.9	
832H13	E9310	14NiCrMo13-4	Carburized	12.7	3.1	19.4	4.7	5.9	45.8	
080M30	1030	C30	Induction hardened	17.0	5.6	16.4	7.6	9.8	56.6	
080M40	1040	C40	Induction hardened	17.6	3.7	17.1	7.1	9.6	55.0	
080M50	1050	C50	Induction hardened	21.2	1.5	20.0	5.9	9.4	58.0	
060A62	1060	C60	Induction hardened	21.4	0.9	19.8	5.9	9.2	57.2	
080A83	1080	--	Induction hardened	20.9	0.6	22.3	5.9	8.8	58.5	
060A96	1095	CK101	Induction hardened	20.5	0.4	24.4	5.9	9.0	60.1	
708M40	4150	50CrMo4	Induction hardened	20.5	2.0	29.3	5.9	8.1	65.6	
530H32	5130	--	Induction hardened	16.2	4.1	25.9	7.9	9.4	63.4	
530M40	5140	41Cr4	Induction hardened	20.9	3.3	27.8	7.1	9.1	68.1	
735A51	6150	50CrV4	Induction hardened	24.3	2.2	29.2	6.5	8.2	70.4	5
945A40	8640	--	Induction hardened	20.9	0.6	28.5	7.1	7.7	64.7	
080M40	1040	C40	H & T at 205	17.6	0.6	17.1	8.2	9.4	52.9	
080M40	1040	C40	H & T at 315	13.7	1.3	17.1	8.2	9.4	49.7	
080M40	1040	C40	H & T at 540	9.4	1.5	15.5	8.2	9.4	44.0	
080M50	1050	C50	H & T at 205	17.6	0.2	20.0	8.2	9.4	55.4	
080M50	1050	C50	H & T at 315	15.2	0.2	19.6	8.2	9.4	52.7	
080M50	1050	C50	H & T at 540	10.1	0.4	16.6	8.2	9.4	44.7	
060A62	1060	C60	H & T at 205	11.1	1.5	19.8	12.7	9.4	54.4	
060A62	1060	C60	H & T at 315	10.7	1.5	19.4	8.2	9.4	53.8	
060A62	1060	C60	H & T at 540	9.6	1.6	18.0	8.2	9.4	51.3	
080A83	1080	--	H & T at 205	13.3	1.1	22.3	8.2	9.4	54.4	
080A83	1080	--	H & T at 315	13.0	1.1	22.1	8.2	9.4	53.8	
080A83	1080	--	H & T at 540	11.1	1.3	20.2	8.2	9.4	50.2	
060A96	1095	CK101	H & T at 205	13.6	0.6	22.1	8.2	9.4	53.9	
060A96	1095	CK101	H & T at 315	13.0	0.6	21.8	8.2	9.4	52.9	
060A96	1095	CK101	H & T at 540	11.1	0.7	19.6	8.2	9.4	49.0	
216M44	1144	--	H & T at 205	9.6	0.7	16.8	10.0	9.5	46.6	
216M44	1144	--	H & T at 315	9.0	0.7	16.7	10.0	9.5	46.0	
216M44	1144	--	H & T at 540	8.2	1.1	15.9	10.0	9.5	44.7	
150M36	1340	36Mn5	H & T at 205	17.2	0.6	27.9	5.9	9.5	61.1	
150M36	1340	36Mn5	H & T at 315	15.4	1.1	25.5	5.9	9.5	57.5	
150M36	1340	36Mn5	H & T at 540	10.2	1.3	18.0	5.9	9.5	44.9	
708A25	4130	25CrMo4	H & T at 205	16.0	2.8	25.8	8.2	8.3	61.1	
708A25	4130	25CrMo4	H & T at 315	14.9	2.8	24.6	8.2	8.3	58.8	
708A25	4130	25CrMo4	H & T at 540	10.9	2.2	18.9	8.2	8.3	48.6	
708M40	4150	50CrMo4	H & T at 205	18.1	1.1	29.3	6.5	8.1	63.0	
708M40	4150	50CrMo4	H & T at 315	16.9	1.2	27.5	6.5	8.1	60.1	
708M40	4150	50CrMo4	H & T at 540	12.7	2.0	21.1	6.5	8.1	50.2	
817M40	4340	34CrNiMo6	H & T at 205	17.7	1.6	28.5	5.9	6.4	60.1	
817M40	4340	34CrNiMo6	H & T at 315	16.6	2.2	27.5	5.9	6.4	58.5	
817M40	4340	34CrNiMo6	H & T at 540	12.7	3.7	20.6	5.9	6.4	49.3	
530M40	5140	41Cr4	H & T at 205	16.7	1.1	27.8	7.6	9.4	62.7	
530M40	5140	41Cr4	H & T at 315	15.3	1.3	25.4	7.6	9.4	59.1	
530M40	5140	41Cr4	H & T at 540	9.7	4.5	18.4	7.6	9.4	49.6	
--	5150	46Cr2	H & T at 205	17.9	1.5	29.4	7.1	9.1	64.9	
--	5150	46Cr2	H & T at 315	16.2	1.4	27.2	7.1	9.1	60.9	
--	5150	46Cr2	H & T at 540	11.8	2.3	20.0	7.1	9.1	50.2	
527H60	5160	--	H & T at 205	21.4	1.6	32.3	6.5	8.9	70.7	4
527H60	5160	--	H & T at 315	18.9	1.6	30.0	6.5	8.9	65.9	
527H60	5160	--	H & T at 540	11.6	4.4	20.5	6.5	8.9	51.9	
735A51	6150	50CrV4	H & T at 205	18.3	1.5	29.3	6.5	8.2	63.8	
735A51	6150	50CrV4	H & T at 315	16.5	1.2	27.0	6.5	8.2	59.4	
735A51	6150	50CrV4	H & T at 540	11.8	3.3	20.5	6.5	8.2	50.2	
708M40	8650	--	H & T at 205	17.9	2.4	29.3	7.1	7.6	64.2	
708M40	8650	--	H & T at 315	16.7	2.8	27.0	7.1	7.6	61.2	
708M40	8650	--	H & T at 540	11.6	3.3	20.6	7.1	7.6	50.2	
805A60	8660	--	H & T at 205	15.7	1.8	26.0	6.5	7.5	57.4	
805A60	8660	--	H & T at 315	12.6	2.8	22.3	6.5	7.5	51.7	
805A60	8660	--	H & T at 540	10.8	3.7	19.3	6.5	7.5	47.8	
823M30	8740	30CrNiMo8	H & T at 205	19.7	3.3	30.0	7.6	7.5	68.2	
823M31	8740	30CrNiMo9	H & T at 315	16.9	3.7	27.0	7.6	7.5	62.7	
823M32	8740	30CrNiMo10	H & T at 540	12.5	3.8	21.1	7.6	7.5	52.5	
708M40	4140 N	42CrMo4	Nitrided	22.3	4.4	21.5	7.1	7.6	62.7	
722M24	--	32CrMo12	Nitrided	27.8	7.9	21.5	7.1	6.9	71.1	3
817M40	4340	34CrNiMo6	Nitrided	20.2	4.4	23.4	7.1	5.8	60.8	
897M39	--	--	Nitrided	33.0	10.0	16.9	6.5	5.7	72.1	2
905M31	**--**	**--**	**Nitrided**	**40.0**	**7.3**	**17.0**	**5.9**	**5.4**	**75.6**	**1**
905M39	--	41CrAlMo7	Nitrided	31.3	7.5	20.5	5.9	5.3	70.4	

5.7.4 Selection of low cost gear steels

5.7.4.1 Relative importance of gear requirements (Weighting factor):

The cost will be considered as the most important property for gear requirements as shown in table (5.14).

Table 5-14 weighting factors for low cost gear steels.

Determination of relative importance of required properties for Low cost gear steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Cost	1	1	1	1							4	0.400
Surface hardness	0				1	1	1				3	0.300
Fatigue strength		0			0			1	0		1	0.100
Machinability			0			0		0		1	1	0.100
Toughness				0			0		1	0	1	0.100
											10	**1.000**

5.7.4.2 Performance index (γ) for low cost gear steels

Performance index calculations are shown that the optimum steel can be used when the cost is first requirement for gear design **is *(BS 905M31*)** steel in nitrided condition.

The ranking list for wear resistance gear steel (highest 5 ranked steels are red colured) is shown in table (5.15).

Table 5-15 performance index & ranking of low cost gear steels

Performance index & Ranking for low cost gear steels										
Steel Grade Standards			Condition	Surface hardness	Toughness	Fatigue strength	Machinability	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
080M15	1015	C15	Carburized	5.9	4.4	4.2	7.1	38.3	60.0	
120M19	1022	C22	Carburized	7.2	3.7	3.8	7.1	40.0	61.8	
214M15	1118	--	Carburized	7.8	7.2	3.9	9.4	38.3	66.6	
665M20	4620	--	Carburized	7.0	2.4	4.2	7.6	26.8	48.1	
815M17	4320	17CrNiMo6	Carburized	11.5	2.5	5.2	8.2	26.4	53.9	
--	4820	--	Carburized	11.1	3.7	5.0	0.0	22.3	42.1	
805M20	8620	21Ni CrMo2	Carburized	10.1	1.2	5.8	7.1	31.3	55.5	
832H13	E9310	14NiCrMo13-4	Carburized	9.5	3.1	6.5	4.7	23.6	47.4	
080M30	1030	C30	Induction hardened	12.8	5.6	5.5	7.6	39.1	70.7	2
080M40	1040	C40	Induction hardened	13.2	3.7	5.7	7.1	38.3	67.9	
080M50	1050	C50	Induction hardened	15.9	1.5	6.7	5.9	37.5	67.4	
060A62	1060	C60	Induction hardened	16.0	0.9	6.6	5.9	36.9	66.3	
080A83	1080	--	Induction hardened	15.7	0.6	7.4	5.9	35.3	64.8	
060A96	1095	CK101	Induction hardened	15.3	0.4	8.1	5.9	35.8	65.6	
708M40	4150	50CrMo4	Induction hardened	15.3	2.0	9.8	5.9	32.2	65.2	
530H32	5130	--	Induction hardened	12.2	4.1	8.6	7.9	37.4	70.2	
530M40	**5140**	**41Cr4**	**Induction hardened**	**15.7**	**3.3**	**9.3**	**7.1**	**36.2**	**71.5**	**1**
735A51	6150	50CrV4	Induction hardened	18.2	2.2	9.7	6.5	32.9	69.5	
945A40	8640	--	Induction hardened	15.7	0.6	9.5	7.1	30.8	63.6	
080M40	1040	C40	H & T at 205	13.2	0.6	5.7	8.2	37.5	65.2	
080M40	1040	C40	H & T at 315	10.3	1.3	5.7	8.2	37.5	63.0	
080M40	1040	C40	H & T at 540	7.1	1.5	5.2	8.2	37.5	59.4	
080M50	1050	C50	H & T at 205	13.2	0.2	6.7	8.2	37.5	65.8	
080M50	1050	C50	H & T at 315	11.4	0.2	6.5	8.2	37.5	63.9	
080M50	1050	C50	H & T at 540	7.6	0.4	5.5	8.2	37.5	59.2	
060A62	1060	C60	H & T at 205	8.3	1.5	6.6	12.7	37.5	66.6	
060A62	1060	C60	H & T at 315	8.1	1.5	6.5	8.2	37.5	66.3	
060A62	1060	C60	H & T at 540	7.2	1.6	6.0	8.2	37.5	65.0	
080A83	1080	--	H & T at 205	10.0	1.1	7.4	8.2	37.5	64.3	
080A83	1080	--	H & T at 315	9.7	1.1	7.4	8.2	37.5	63.9	
080A83	1080	--	H & T at 540	8.3	1.3	6.7	8.2	37.5	62.1	
060A96	1095	CK101	H & T at 205	10.2	0.6	7.4	8.2	37.5	63.9	
060A96	1095	CK101	H & T at 315	9.7	0.6	7.3	8.2	37.5	63.3	
060A96	1095	CK101	H & T at 540	8.3	0.7	6.5	8.2	37.5	61.2	
216M44	1144	--	H & T at 205	7.2	0.7	5.6	10.0	38.1	61.6	
216M44	1144	--	H & T at 315	6.8	0.7	5.6	10.0	38.1	61.2	
216M44	1144	--	H & T at 540	6.1	1.1	5.3	10.0	38.1	60.6	
150M36	1340	36Mn5	H & T at 205	12.9	0.6	9.3	5.9	38.1	66.8	
150M36	1340	36Mn5	H & T at 315	11.6	1.1	8.5	5.9	38.1	65.2	
150M36	1340	36Mn5	H & T at 540	7.7	1.3	6.0	5.9	38.1	58.9	
708A25	4130	25CrMo4	H & T at 205	12.0	2.8	8.6	8.2	33.4	64.9	
708A25	4130	25CrMo4	H & T at 315	11.1	2.8	8.2	8.2	33.4	63.8	
708A25	4130	25CrMo4	H & T at 540	8.2	2.2	6.3	8.2	33.4	58.3	
708M40	4150	50CrMo4	H & T at 205	13.6	1.1	9.8	6.5	32.2	63.2	
708M40	4150	50CrMo4	H & T at 315	12.7	1.2	9.2	6.5	32.2	61.7	
708M40	4150	50CrMo4	H & T at 540	9.5	2.0	7.0	6.5	32.2	57.2	
817M40	4340	34CrNiMo6	H & T at 205	13.3	1.6	9.5	5.9	25.4	55.8	
817M40	4340	34CrNiMo6	H & T at 315	12.4	2.2	9.2	5.9	25.4	55.1	
817M40	4340	34CrNiMo6	H & T at 540	9.5	3.7	6.9	5.9	25.4	51.5	
530M40	5140	41Cr4	H & T at 205	12.5	1.1	9.3	7.6	37.4	68.0	
530M40	5140	41Cr4	H & T at 315	11.5	1.3	8.5	7.6	37.4	66.4	
530M40	5140	41Cr4	H & T at 540	7.3	4.5	6.1	7.6	37.4	63.0	
--	5150	46Cr2	H & T at 205	13.4	1.5	9.8	7.1	36.2	68.0	
--	5150	46Cr2	H & T at 315	12.2	1.4	9.1	7.1	36.2	65.9	
--	5150	46Cr2	H & T at 540	8.8	2.3	6.7	7.1	36.2	61.1	
527H60	5160	--	H & T at 205	16.0	1.6	10.8	6.5	35.6	70.5	3
527H60	5160	--	H & T at 315	14.2	1.6	10.0	6.5	35.6	67.8	
527H60	5160	--	H & T at 540	8.7	4.4	6.8	6.5	35.6	62.0	
735A51	6150	50CrV4	H & T at 205	13.7	1.5	9.8	6.5	32.9	64.4	
735A51	6150	50CrV4	H & T at 315	12.3	1.2	9.0	6.5	32.9	61.9	
735A51	6150	50CrV4	H & T at 540	8.8	3.3	6.8	6.5	32.9	58.3	
708M40	8650	--	H & T at 205	13.4	2.4	9.8	7.1	30.3	62.9	
708M40	8650	--	H & T at 315	12.5	2.8	9.0	7.1	30.3	61.7	
708M40	8650	--	H & T at 540	8.7	3.3	6.9	7.1	30.3	56.3	
805A60	8660	--	H & T at 205	11.8	1.8	8.7	6.5	29.9	58.6	
805A60	8660	--	H & T at 315	9.5	2.8	7.4	6.5	29.9	56.1	
805A60	8660	--	H & T at 540	8.1	3.7	6.4	6.5	29.9	54.6	
823M30	8740	30CrNiMo8	H & T at 205	14.8	3.3	10.0	7.6	30.1	65.8	
823M30	8740	30CrNiMo8	H & T at 315	12.7	3.7	9.0	7.6	30.1	63.0	
823M30	8740	30CrNiMo8	H & T at 540	9.3	3.8	7.0	7.6	30.1	57.9	
708M40	4140 N	42CrMo4	Nitrided	16.7	4.4	7.2	7.1	30.2	65.5	
722M24	--	32CrMo12	Nitrided	20.9	7.9	7.2	7.1	27.5	70.4	4
817M40	4340	34CrNiMo6	Nitrided	15.1	4.4	7.8	7.1	23.1	57.5	
897M39	--	--	Nitrided	24.8	10.0	5.6	6.5	22.8	69.7	
905M31	--	--	Nitrided	30.0	7.3	5.7	5.9	21.6	70.5	3
905M39	--	41CrAlMo7	Nitrided	23.5	7.5	6.8	5.9	21.0	64.7	

Chapter 6

6 SELECTION OF SHAFT STEELS

6.1 Definition of shaft

The shaft is fixed or rotating component which is normally circular in section.

A shaft is usually designed transfer torque from a driving component to another driving component.

If the shaft is rotating, it is the transferring power, and if a shaft operating without rotary motion is transmitting torque.

Gears, couplings, pulleys, cams, sprockets, links and flywheels are common mechanical components directly attached to the shaft, and the torque is normally transmitted to the attached components using pins, keys, clamping bushes; press fits, bonded joints and sometimes welded connections are used. A shaft is normally supported on bearings [34].

6.2 Types of shafts

The shafts can be classified as:

- Straight shaft (Constant diameter or Stepped): carry rotating member such as gears, pulley, or other wheels, figure (6.1).
- Crankshaft: crankshaft is used to convert reciprocating motion into rotary motion or vice versa, figure (6.2) [35].

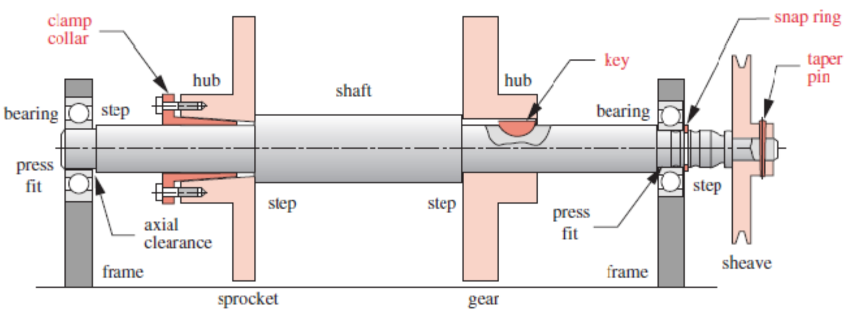


Figure 6-1 Typical straight (stepped) shaft and with various attachments [36]

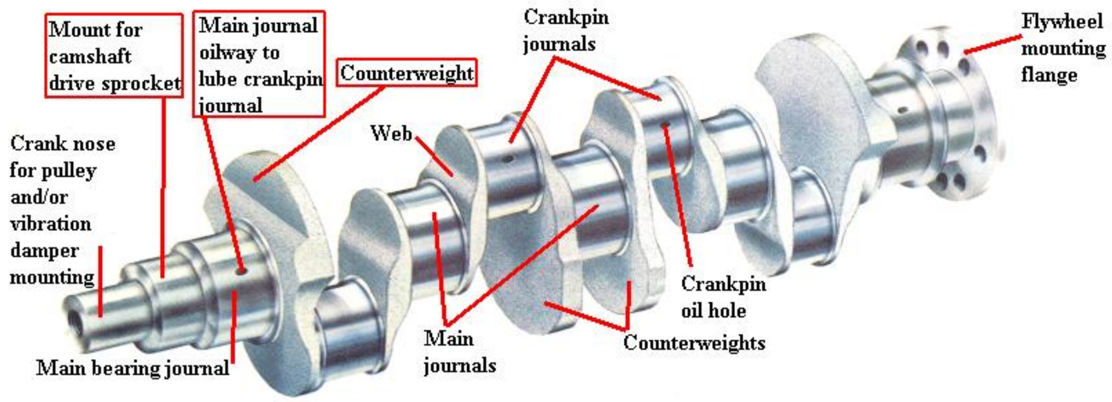


Figure 6-2 Crankshaft with various attachments [36]

6.3 Mechanical properties requirements for shaft

Most shafts are under fluctuating loads of combined bending and torsion with various degrees of stress concentrations. Most shafts are not subjected to shock or impact loading. However, some applications of static strength, fatigue strength, and reliability play a significant role in shaft design [36].

In addition to satisfying strength requirements, shaft must be designed so that deflections are within acceptable limits. Excessive lateral shaft deflections can hamper gear performance and cause objectionable noise. Tensional deflection can affect the accuracy of a cam-or gear-driven mechanism [37]. The Figure (6.3) shows typical loads applied to a shaft during power transmission and the resultant deflections. Not all the loads shown will be present in every case.

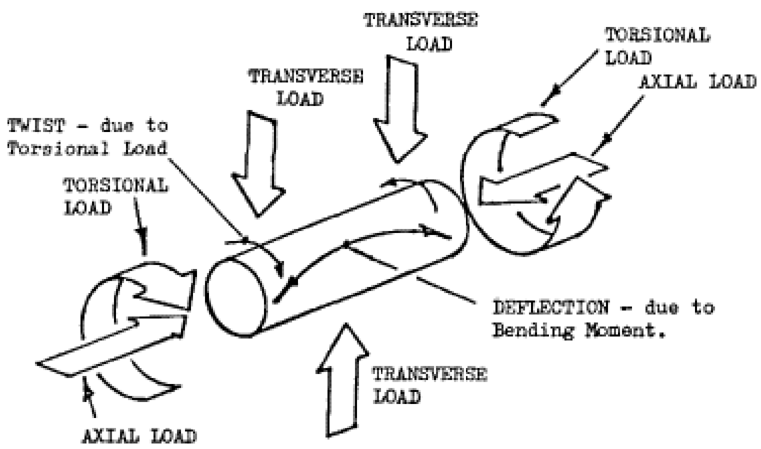


Figure 6-3 Typical loads applied to a shaft [39]

6.3.1 Mechanical properties required

Most shafts require the following mechanical properties:

- High strength to withstand the high loads.
- Resistance to fatigue in both shear and bending.
- Resistance to wear in the bearing areas.

6.4 Steels for shafts

In order to select steel, the shaft should have good mechanical properties to withstand loads. It should be able to hold a large amount of force to prevent it from bending and it should have a small angle of twist. If it has a big deflection, the gears could separate from each other, causing them to not function properly or to wear off.

Most steels have similar moduli of elasticity, so that the rigidity requirement can be met by geometric decisions, independent of the material choice among steels.

Strength to resist loading stresses affects the choice of material. AISI 1020-1050 steels and HXX free-machining steels are common choices. Heat treating 1340-50, 3140-50, 4140, 4340, 5140, and 8650 steels produces greater strength.

Carburizing grades 1020, 4320, 4820, and 8620 are chosen for surface-hardening purposes. Tables (6.1, 6.2, 6.3, & 6.4) show the chemical composition and mechanical properties of heat treatments shaft steels [39].

Table 6-1 Chemical composition of shaft steels [24], [25], [26] [27]

Steel Grade Standards			Chemical Compositions of Shaft Steels %								
BS	AISI	DIN	C	Mn	P	S	Si	Ni	Cr	Mo	Others
070M20	1022	C22	0.17-0.23	0.70-1.00	0.04	0.05	--	--	--	--	--
070M26	1025	C25	0.22-0.28	0.30-0.60	0.03	0.05	--	--	--	--	--
080M30	1030	C30	0.28-0.34	0.60-0.90	0.04	0.05	--	--	--	--	--
080M40	1040	C40	0.37-0.44	0.60-0.90	0.04	0.05	--	--	--	--	--
060A62	1060	C60	0.55-0.65	0.60-0.90	0.04	0.05	--	--	--	--	--
150M36	1340	36Mn5	0.38-0.43	1.60-1.90	0.035	0.04	0.15-0.35	--	--	--	--
--	3140	40NiCr6	0.38-0.43	0.70-0.90	0.04	0.04	0.20-0.35	1.10-1.40	0.55-0.75	--	--
--	3150	--	0.48-0.53	0.70-0.90	0.04	0.04	0.20-0.35	1.10-1.40	0.55-0.75	--	--
653M31	3325	28NiCr10	0.27-0.35	0.45-0.70	0.04	0.10-0.35	--	2.75-3.25	0.90-1.20	--	--
708A40	4130	25MoCr4	0.28-0.33	0.40-0.60	0.04	0.04	0.10-0.35		0.80-1.10	0.15-0.25	
708M40	4140	42CrMo4	0.38-0.43	0.75-1.00	0.035	0.04	0.15-0.35	--	0.80-1.10	0.15-0.25	--
815M17	4320	17CrNiMo6	0.17-0.22	0.45-0.65	0.035	0.04	0.15-0.35	1.65-2.00	0.40-0.60	0.20-0.30	--
817M40	4340	34CrNiMo6	0.38-0.43	0.60-0.80	0.035	0.04	0.15-0.35	1.65-2.00	0.70-0.90	0.20-0.30	--
665M20	4620	--	0.17-0.22	0.45-0.65	0.035	0.04	0.15-0.35	1.65-2.00	--	0.20-0.30	--
--	4820	--	0.18-0.23	0.50-0.70	0.035	0.04	0.15-0.35	3.25-3.75	--	0.20-0.30	--
530M40	5140	41Cr4	0.38-0.43	0.70-0.90	0.035	0.04	0.15-0.30	--	0.70-0.90	--	--
--	5150	46Cr2	0.48-0.53	0.70-0.90	0.035	0.04	0.15-0.30	--	0.70-0.90	--	--
735A51	6150	50CrV4	0.48-0.53	0.70-0.90	0.035	0.04	0.15-0.30	--	0.80-1.10	--	V 0.15 min.
805M20	8620	21Ni CrMo2	0.18-0.23	0.70-0.90	0.035	0.04	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	
708M40	8650	--	0.48-0.53	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25	--
823M30	8740	30CrNiMo8	0.38-0.43	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.20-0.30	--
722M24	--	32CrMo12	0.36-0.44	0.45-0.70	0.035	0.04	0.10-0.35	--	3.00-3.50	0.45-0.65	--
897M39	--	39CrMoV139	0.35-0.43	0.45-0.70	0.02	0.02	--	--	3.00-3.50	0.80-1.10	V 0.15-0.25
905M39	--	42CrAlMo7	0.38-0.45	0.50-0.80	0.03	0.03	0.20-0.40	--	1.50-1.30	0.25-0.40	Al 0.90-1.30
976M33	--	--	0.28-0.38	0.20-0.60	0.04	0.04	0.10-0.35	2.90-3.60	0.90-1.70	0.45-0.65	V0.08-0.15

Table 6-2 Mechanical properties of carburized shaft steels [4], [13], [24], [25], [26], [27], [30], [31]

Steel Grade Standards			[1]Mechanical Properties as Carburizing treatment							[2]Cost $/Kg $*10^{-1}$
BS	AISI	DIN	σ_{uts} Mpa	σ_y Mpa	Elong%	Bending Fatigue strength at 10^7 cycle Mpa	3Shear Fatigue strength at 10^7 cycle Mpa	Hardness HV	[2]Machinability %	
120M19	1022	C22	483	358	26	290	145	276	80	0.961
815M17	4320	17CrNiMo6	793	465	21	476	238	440	70	1.152
665M20	4620	--	575	368	29	345	173	269	65	1.135
--	4820	--	753	485	22	452	226	425	50	1.365
805M20	8620	21Ni CrMo2	860	565	23	516	258	388	60	0.972

[1] Gas Carburizing at 915 ^{0}C, for 8 hours, 775 ^{0}C reheat, Water quench, 175 ^{0}C temper.

[2] Cost is included row steel price and heat treatment cost (10% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[3] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

[4] Shear Fatigue is calculated from $\tau_0 = 0.3\ \sigma_{uts}$ [34]

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength (or 0.2% Proof stress)

Table 6-3 Mechanical properties of nitrided shaft steels [4], [13], [24], [25], [26], [27], [30], [31]

Steel Grade Standards			Core Treatment		[1]Mechanical Properties as Nitriding Treatment							[2]Cost $/Kg *$10^{-1}$
BS	AISI	DIN	Hardening Temp. ^{0}C oil quench	Tempering Temp. ^{0}C	σ_{uts} Mpa	σ_y Mpa	Elong %	Bending Fatigue strength at 10^7 cycle , Mpa	[4]Shear Fatigue strength at 10^7 cycle , Mpa	Hardness HV	[3]Machinability %	
708M40	4140	42CrMo4	860	500	1080	765	11	497	324	640	60	1.007
722M24	--	32CrMo12	900	570	1080	785	11	497	324	800	60	1.109
817M40	4340	34CrNiMo6	840	550	1180	885	10	543	354	580	60	1.317
897M39	--	--	920	600	850	660	13	391	255	950	55	1.333
905M31	--	--	920	570	855	590	14	393	257	1150	50	1.410
905M39	--	41CrAlMo7	920	600	1030	735	17	474	309	900	50	1.450

[1] Gas Nitriding at 520 ^{0}C, for 48 hours.

[2] Cost is included row steel price and heat treatment cost (10% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[3] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

[4] Shear Fatigue is calculated from $\tau_0 = 0.3\ \sigma_{uts}$ [34]

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength (or 0.2% Proof stress)

Table 6-4 Mechanical properties of through hardened shaft steels [4], [12], [20], [21], [22], [27], [28]

Steel Grade Standards			Heat Treatment		Mechanical Properties as Through Hardening Condition							[1]Cost $/Kg *$10^{-1}$
BS	AISI	DIN	Quenching ^{0}C (medium)	Tempering ^{0}C	σ_{uts} Mpa	σ_y Mpa	Elong%	Bending Fatigue strength at 10^7 cycle, Mpa	[3]Shear Fatigue strength at 10^7 cycle, Mpa	Hardness HV	[2]Machinability %	
080M40	1040	C40	845 (Water)	205	898	663	16	397	270	505	70	0.812
				315	893	648	18	395	268	395	70	
				540	780	593	23	360	234	271	70	
080M50	1050	C50	830 (Water)	205	1123	808	9	464	337	505	70	0.812
				315	1090	793	13	455	327	436	70	
				540	860	655	23	385	258	290	70	
060A62	1060	C60	830 (Oil)	205	1103	780	13	458	331	319	70	0.812
				315	1077	765	14	450	323	309	70	
				540	965	670	17	417	290	275	70	
150M36	1340	36Mn5	830 (Oil)	205	1808	1593	11	647	542	495	50	0.800
				315	1588	1420	12	591	476	444	50	
				540	965	828	17	417	290	294	50	
708A25	4130	25CrMo4	855 (Water)	205	1610	1463	10	597	483	459	70	0.912
				315	1498	1380	11	569	449	427	70	
				540	1033	910	17	438	310	314	70	
530M40	5140	41Cr4	845 (Oil)	205	1793	1640	9	644	538	481	65	0.813
				315	1508	1448	10	589	452	441	65	
				540	1000	863	17	427	300	279	65	
--	5150	46Cr2	830 (Oil)	205	1945	1730	5	681	584	515	60	0.841
				315	1738	1608	6	630	521	466	60	
				540	1123	1033	15	464	337	338	60	
735A51	6150	50CrV4	845 (Oil)	205	1930	1690	8	678	579	527	55	0.927
				315	1725	1573	8	626	518	473	55	
				540	1158	1070	13	474	347	338	55	
708M40	8650	--	800 (Oil)	205	1938	1670	10	679	581	515	60	1.005
				315	1725	1550	10	626	518	481	60	
				540	1173	1053	15	478	352	333	60	
823M30	8740	30CrNiMo8	830 (Oil)	205	2000	1655	10	695	600	566	65	1.013
				315	1718	1550	11	625	515	486	65	
				540	1208	1138	15	488	362	358	65	

[1] Cost is included row steel price and heat treatment cost (5% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[2] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

[3] Shear Fatigue is calculated from $\tau_0 = 0.3\ \sigma_{uts}$, [34]

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength (or 0.2% Proof stress)

6.5 Selection of shaft steels by using weighted property method

All design requirements for shafts, yield strength, bending fatigue strength; shear fatigue strength, hardness, and cost are scaled by using Eq. (4.1 & 4.2) as discussed in chapter 4. These scaled properties are listed in table (6.5).

Table 6-5 scaled value for each property

Steel Grade Standards			Condition	Scaled values of Shaft Steels				
				Scaled property				
BS	AISI	DIN		Yield strength, σy	Bending Fatigue strength.	Shear Fatigue strength.	Hardness	Cost
120M19	1022	C22	carburized	20.69	41.73	24.17	24	83.19
815M17	4320	17CrNiMo6	carburized	26.88	68.49	39.67	38.26	69.4
665M20	4620	--	carburized	21.27	49.64	28.83	23.39	70.44
--	4820	--	carburized	28.03	65.04	37.67	36.96	58.57
805M20	8620	21Ni CrMo2	carburized	32.66	74.24	43	33.74	82.26
080M40	1040	C40	H & T at 540	38.32	57.12	45	43.91	98.41
080M40	1040	C40	H & T at 205	37.46	56.83	44.67	34.35	98.41
080M40	1040	C40	H & T at 315	34.28	51.8	39	23.57	98.41
080M50	1050	C50	H & T at 540	46.71	66.76	56.17	43.91	98.41
080M50	1050	C50	H & T at 205	45.84	65.47	54.5	37.91	98.41
080M50	1050	C50	H & T at 315	37.86	78.89	43	25.22	98.41
060A62	1060	C60	H & T at 540	45.09	65.9	55.17	27.74	98.41
060A62	1060	C60	H & T at 205	44.22	64.75	53.83	26.87	98.41
060A62	1060	C60	H & T at 315	38.73	60	48.33	23.91	98.41
150M36	1340	36Mn5	H & T at 540	92.08	93.09	90.33	43.04	100
150M36	1340	36Mn5	H & T at 205	82.08	85.04	79.33	38.61	100
150M36	1340	36Mn5	H & T at 315	47.86	60	48.33	25.57	100
708A25	4130	25CrMo4	H & T at 540	84.57	85.9	80.5	39.91	87.64
708A25	4130	25CrMo4	H & T at 205	79.77	81.87	74.83	37.13	87.64
708A25	4130	25CrMo4	H & T at 315	52.6	63.02	51.67	27.3	87.64
530M40	5140	41Cr4	H & T at 540	94.8	92.66	89.67	41.83	98.29
530M40	5140	41Cr4	H & T at 205	83.7	84.75	75.33	38.35	98.29
530M40	5140	41Cr4	H & T at 315	49.88	61.44	50	24.26	98.29
--	5150	46Cr2	H & T at 540	100	97.99	97.33	44.78	95.09
--	5150	46Cr2	H & T at 205	92.95	90.65	86.83	40.52	95.09
--	5150	46Cr2	H & T at 315	59.71	66.76	56.17	29.39	95.09
735A51	6150	50CrV4	H & T at 540	97.69	97.55	96.5	45.83	86.26
735A51	6150	50CrV4	H & T at 205	90.92	90.07	86.33	41.13	86.26
735A51	6150	50CrV4	H & T at 315	61.85	68.2	57.83	29.39	86.26
708M40	8650	--	H & T at 540	96.53	97.7	96.83	44.78	79.55
708M40	8650	--	H & T at 205	89.6	90.07	86.33	41.83	79.55
708M40	8650	--	H & T at 315	60.87	68.78	58.67	28.96	79.55
823M30	8740	30CrNiMo8	H & T at 540	95.66	100	100	49.22	78.92
823M30	8740	30CrNiMo8	H & T at 205	89.6	89.93	85.83	42.26	78.92
823M30	8740	30CrNiMo8	H & T at 315	65.78	70.22	60.33	31.13	78.92
708M40	4140	42CrMo4	Nitrided	44.22	71.51	54	55.65	79.39
722M24	--	32CrMo12	Nitrided	45.38	71.51	54	69.57	72.09
817M40	4340	34CrNiMo6	Nitrided	51.16	78.13	59	50.43	60.71
897M39	--	--	Nitrided	38.15	56.26	42.5	82.61	59.98
905M31	--	--	Nitrided	34.1	56.55	42.83	100	56.7
905M39	--	41CrAlMo7	Nitrided	42.49	68.2	51.5	78.26	55.14
	Maximum scaled property of Shaft Steels							

6.5.1 Selection of high strength shaft steels

6.5.1.1 Relative importance of shaft requirements (Weighting factor)

The digital logic method is used to determine the weighting factors (α). With five requirements for shaft design to evaluate, the total number of decisions is *N (N-1)/2= 5(4)/2=10*. The different decisions are given in Table (6.6).

Table 6-6 Weighting factors for high strength gear steels.

Determination of relative importance of required properties for High strength shaft steels by using the digital logic method													
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	1	1	1	1							4	0.400
Bending Fatigue strength.	0				0			1	1		2	0.200
Shear Fatigue strength.		0			1	1	0				2	0.200
Hardness			0			0		0		1	1	0.100
Cost				0			1		0	0	1	0.100
											10	**1.000**

6.5.1.2 Performance index (γ) for fatigue strength gear steels

By using Eq. (4.3) the performance index for each property will be calculated and ranking will be made according to performance index for individual steel (highest 5 ranked steels are red colured), as shown in Table (6.7).

The results shows that (***AISI 5150, DIN 46Cr2)*** steel in a hardened and tempered at 205 ^{0}C is the optimum choice for high strength shaft steels

Table 6-7 performance index & ranking of high strength shaft steels

Performance index & Ranking for High strength shaft steels										
Steel Grade Standards			Condition	σy	Bending Fatigue strength	Shear Fatigue strength	Hardness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
120M19	1022	C22	carburized	8.3	8.3	4.8	2.4	8.3	32.2	
815M17	4320	17CrNiMo6	carburized	10.8	13.7	7.9	3.8	6.9	43.1	
665M20	4620	--	carburized	8.5	9.9	5.8	2.3	7.0	33.6	
--	4820	--	carburized	11.2	13.0	7.5	3.7	5.9	41.3	
805M20	8620	21Ni CrMo2	carburized	13.1	14.8	8.6	3.4	8.2	48.1	
080M40	1040	C40	H & T at 205	15.3	11.4	9.0	4.4	9.8	50.0	
080M40	1040	C40	H & T at 315	15.0	11.4	8.9	3.4	9.8	48.6	
080M40	1040	C40	H & T at 540	13.7	10.4	7.8	2.4	9.8	44.1	
080M50	1050	C50	H & T at 205	18.7	13.4	11.2	4.4	9.8	57.5	
080M50	1050	C50	H & T at 315	18.3	13.1	10.9	3.8	9.8	56.0	
080M50	1050	C50	H & T at 540	15.1	15.8	8.6	2.5	9.8	51.9	
060A62	1060	C60	H & T at 205	18.0	13.2	11.0	2.8	9.8	54.9	
060A62	1060	C60	H & T at 315	17.7	12.9	10.8	2.7	9.8	53.9	
060A62	1060	C60	H & T at 540	15.5	12.0	9.7	2.4	9.8	49.4	
150M36	1340	36Mn5	H & T at 205	36.8	18.6	18.1	4.3	10.0	87.8	4
150M36	1340	36Mn5	H & T at 315	32.8	17.0	15.9	3.9	10.0	79.6	
150M36	1340	36Mn5	H & T at 540	19.1	12.0	9.7	2.6	10.0	53.4	
708A25	4130	25CrMo4	H & T at 205	33.8	17.2	16.1	4.0	8.8	79.9	
708A25	4130	25CrMo4	H & T at 315	31.9	16.4	15.0	3.7	8.8	75.7	
708A25	4130	25CrMo4	H & T at 540	21.0	12.6	10.3	2.7	8.8	55.5	
530M40	5140	41Cr4	H & T at 205	37.9	18.5	17.9	4.2	9.8	88.4	4
530M40	5140	41Cr4	H & T at 315	33.5	16.9	15.1	3.8	9.8	79.2	
530M40	5140	41Cr4	H & T at 540	20.0	12.3	10.0	2.4	9.8	54.5	
--	**5150**	**46Cr2**	**H & T at 205**	**40.0**	**19.6**	**19.5**	**4.5**	**9.5**	**93.1**	**1**
--	5150	46Cr2	H & T at 315	37.2	18.1	17.4	4.1	9.5	86.2	5
--	5150	46Cr2	H & T at 540	23.9	13.4	11.2	2.9	9.5	60.9	
735A51	6150	50CrV4	H & T at 205	39.1	19.5	19.3	4.6	8.6	91.1	2
735A51	6150	50CrV4	H & T at 315	36.4	18.0	17.3	4.1	8.6	84.4	
735A51	6150	50CrV4	H & T at 540	24.7	13.6	11.6	2.9	8.6	61.5	
708M40	8650	--	H & T at 205	38.6	19.5	19.4	4.5	8.0	90.0	3
708M40	8650	--	H & T at 315	35.8	18.0	17.3	4.2	8.0	83.3	
708M40	8650	--	H & T at 540	24.3	13.8	11.7	2.9	8.0	60.7	
823M30	8740	30CrNiMo8	H & T at 205	38.3	20.0	20.0	4.9	7.9	91.1	2
823M30	8740	30CrNiMo8	H & T at 315	35.8	18.0	17.2	4.2	7.9	83.1	
823M30	8740	30CrNiMo8	H & T at 540	26.3	14.0	12.1	3.1	7.9	63.4	
708M40	4140	42CrMo4	Nitrided	17.7	14.3	10.8	5.6	7.9	56.3	
722M24	--	32CrMo12	Nitrided	18.2	14.3	10.8	7.0	7.2	57.4	
817M40	4340	34CrNiMo6	Nitrided	20.5	15.6	11.8	5.0	6.1	59.0	
897M39	--	--	Nitrided	15.3	11.3	8.5	8.3	6.0	49.3	
905M31	--	--	Nitrided	13.6	11.3	8.6	10.0	5.7	49.2	
905M39	--	41CrAlMo7	Nitrided	17.0	13.6	10.3	7.8	5.5	54.3	

6.5.2 Selection of fatigue strength shaft steels

6.5.2.1 Relative importance of shaft requirements (Weighting factor)

By using the digital logic method the weighing factor (α) for shaft requirements are calculated, where the fatigue strength considered as highest importance requirement, as shown in Table (6.8).

Table 6-8 Weighting factors for fatigue strength shaft steels

Determination of relative importance of required properties for Fatigue strength shaft steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	0	1	1	0							2	0.200
Bending Fatigue St.	1				1			1	1		4	0.400
Shear Fatigue St.		0			0	1	1				2	0.200
Hardness			0			0		0		1	1	0.100
Cost				1			0		0	0	1	0.100
											10	**1.000**

6.5.2.2 Performance index (γ) for fatigue strength shaft steels

Performance index calculations are shown that the optimum steel can be used for shaft, when the fatigue strength is the first requirement for shaft design is ***(AISI 5150, DIN 46Cr2)*** steel in hardened and tempered at 205 ^{0}C. The ranking list (Highest 5 ranked steels are red colured) for this application is shown in Table (6.9).

Table 6-9 performance index & ranking of fatigue strength shaft steels

Performance index & Ranking for Fatigue strength shaft steels										
Steel Grade Standards			Condition	σy	Bending Fatigue strength	Shear Fatigue strength	Hardness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
120M19	1022	C22	carburized	4.1	16.7	4.8	2.4	8.3	36.4	
815M17	4320	17CrNiMo6	carburized	5.4	27.4	7.9	3.8	6.9	51.5	
665M20	4620	--	carburized	4.3	19.9	5.8	2.3	7.0	39.3	
--	4820	--	carburized	5.6	26.0	7.5	3.7	5.9	48.7	
805M20	8620	21Ni CrMo2	carburized	6.5	29.7	8.6	3.4	8.2	56.4	
080M40	1040	C40	H & T at 205	7.7	22.8	9.0	4.4	9.8	53.7	
080M40	1040	C40	H & T at 315	7.5	22.7	8.9	3.4	9.8	52.4	
080M40	1040	C40	H & T at 540	6.9	20.7	7.8	2.4	9.8	47.6	
080M50	1050	C50	H & T at 205	9.3	26.7	11.2	4.4	9.8	61.5	
080M50	1050	C50	H & T at 315	9.2	26.2	10.9	3.8	9.8	59.9	
080M50	1050	C50	H & T at 540	7.6	31.6	8.6	2.5	9.8	60.1	
060A62	1060	C60	H & T at 205	9.0	26.4	11.0	2.8	9.8	59.0	
060A62	1060	C60	H & T at 315	8.8	25.9	10.8	2.7	9.8	58.0	
060A62	1060	C60	H & T at 540	7.7	24.0	9.7	2.4	9.8	53.6	
150M36	1340	36Mn5	H & T at 205	18.4	37.2	18.1	4.3	10.0	88.0	5
150M36	1340	36Mn5	H & T at 315	16.4	34.0	15.9	3.9	10.0	80.2	
150M36	1340	36Mn5	H & T at 540	9.6	24.0	9.7	2.6	10.0	55.8	
708A25	4130	25CrMo4	H & T at 205	16.9	34.4	16.1	4.0	8.8	80.1	
708A25	4130	25CrMo4	H & T at 315	16.0	32.7	15.0	3.7	8.8	76.1	
708A25	4130	25CrMo4	H & T at 540	10.5	25.2	10.3	2.7	8.8	57.6	
530M40	5140	41Cr4	H & T at 205	19.0	37.1	17.9	4.2	9.8	88.0	5
530M40	5140	41Cr4	H & T at 315	16.7	33.9	15.1	3.8	9.8	79.4	
530M40	5140	41Cr4	H & T at 540	10.0	24.6	10.0	2.4	9.8	56.8	
--	**5150**	**46Cr2**	**H & T at 205**	**20.0**	**39.2**	**19.5**	**4.5**	**9.5**	**92.6**	**1**
--	5150	46Cr2	H & T at 315	18.6	36.3	17.4	4.1	9.5	85.8	
--	5150	46Cr2	H & T at 540	11.9	26.7	11.2	2.9	9.5	62.3	
735A51	6150	50CrV4	H & T at 205	19.5	39.0	19.3	4.6	8.6	91.1	3
735A51	6150	50CrV4	H & T at 315	18.2	36.0	17.3	4.1	8.6	84.2	
735A51	6150	50CrV4	H & T at 540	12.4	27.3	11.6	2.9	8.6	62.8	
708M40	8650	--	H & T at 205	19.3	39.1	19.4	4.5	8.0	90.2	4
708M40	8650	--	H & T at 315	17.9	36.0	17.3	4.2	8.0	83.4	
708M40	8650	--	H & T at 540	12.2	27.5	11.7	2.9	8.0	62.3	
823M30	8740	30CrNiMo8	H & T at 205	19.1	40.0	20.0	4.9	7.9	91.9	2
823M30	8740	30CrNiMo8	H & T at 315	17.9	36.0	17.2	4.2	7.9	83.2	
823M30	8740	30CrNiMo8	H & T at 540	13.2	28.1	12.1	3.1	7.9	64.3	
708M40	4140	42CrMo4	Nitrided	8.8	28.6	10.8	5.6	7.9	61.8	
722M24	--	32CrMo12	Nitrided	9.1	28.6	10.8	7.0	7.2	62.6	
817M40	4340	34CrNiMo6	Nitrided	10.2	31.3	11.8	5.0	6.1	64.4	
897M39	--	--	Nitrided	7.6	22.5	8.5	8.3	6.0	52.9	
905M31	--	--	Nitrided	6.8	22.6	8.6	10.0	5.7	53.7	
905M39	--	41CrAlMo7	Nitrided	8.5	27.3	10.3	7.8	5.5	59.4	

6.5.3 Selection of wear resistance shaft steels

6.5.3.1 Relative importance of shaft requirements (Weighting factor)

By using a digital logic method a weighing factor (α) for each property will be determined as shown in Table (6.10).

Table 6-10 Weighting factors for wear resistance shaft steels

Determination of relative importance of required properties for Wear Resistance shaft steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	0	0	0	1							1	0.100
Bending Fatigue St.	1				1			0	0		2	0.200
Shear Fatigue St.		1			0	0	1				2	0.200
Hardness			1			1		1		1	4	0.400
Cost				0			0		1	0	1	0.100
											10	**1.000**

6.5.3.2 Performance index (γ) for wear resistance shaft steels:

From the table (6.11) it's clear that ***(BS 823M30, AISI 8740, DIN 30CrNiMo8***) steel is the best steel can be used for wear resistance shaft steels in hardened and tempered at 205 ^{0}C condition .

The ranking list (highest 5 ranked steels are red colured) is made as in table (6.11).

Table 6-11 performance index & ranking of wear resistance shaft steels

Performance index & Ranking for wear resistance shaft steels										
Steel Grade Standards			Condition	σy	Bending Fatigue strength	Shear Fatigue strength	Hardness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
120M19	1022	C22	carburized	2.1	8.3	4.8	9.6	8.3	33.2	
815M17	4320	17CrNiMo6	carburized	2.7	13.7	7.9	15.3	6.9	46.6	
665M20	4620	--	carburized	2.1	9.9	5.8	9.4	7.0	34.2	
--	4820	--	carburized	2.8	13.0	7.5	14.8	5.9	44.0	
805M20	8620	21Ni CrMo2	carburized	3.3	14.8	8.6	13.5	8.2	48.4	
080M40	1040	C40	H & T at 205	3.8	11.4	9.0	17.6	9.8	51.7	
080M40	1040	C40	H & T at 315	3.7	11.4	8.9	13.7	9.8	47.6	
080M40	1040	C40	H & T at 540	3.4	10.4	7.8	9.4	9.8	40.9	
080M50	1050	C50	H & T at 205	4.7	13.4	11.2	17.6	9.8	56.7	
080M50	1050	C50	H & T at 315	4.6	13.1	10.9	15.2	9.8	53.6	
080M50	1050	C50	H & T at 540	3.8	15.8	8.6	10.1	9.8	48.1	
060A62	1060	C60	H & T at 205	4.5	13.2	11.0	11.1	9.8	49.7	
060A62	1060	C60	H & T at 315	4.4	12.9	10.8	10.7	9.8	48.7	
060A62	1060	C60	H & T at 540	3.9	12.0	9.7	9.6	9.8	44.9	
150M36	1340	36Mn5	H & T at 205	9.2	18.6	18.1	17.2	10.0	73.1	4
150M36	1340	36Mn5	H & T at 315	8.2	17.0	15.9	15.4	10.0	66.5	
150M36	1340	36Mn5	H & T at 540	4.8	12.0	9.7	10.2	10.0	46.7	
708A25	4130	25CrMo4	H & T at 205	8.5	17.2	16.1	16.0	8.8	66.5	
708A25	4130	25CrMo4	H & T at 315	8.0	16.4	15.0	14.9	8.8	62.9	
708A25	4130	25CrMo4	H & T at 540	5.3	12.6	10.3	10.9	8.8	47.9	
530M40	5140	41Cr4	H & T at 205	9.5	18.5	17.9	16.7	9.8	72.5	4
530M40	5140	41Cr4	H & T at 315	8.4	16.9	15.1	15.3	9.8	65.6	
530M40	5140	41Cr4	H & T at 540	5.0	12.3	10.0	9.7	9.8	46.8	
--	5150	46Cr2	H & T at 205	10.0	19.6	19.5	17.9	9.5	76.5	2
--	5150	46Cr2	H & T at 315	9.3	18.1	17.4	16.2	9.5	70.5	5
--	5150	46Cr2	H & T at 540	6.0	13.4	11.2	11.8	9.5	51.8	
735A51	6150	50CrV4	H & T at 205	9.8	19.5	19.3	18.3	8.6	75.5	2
735A51	6150	50CrV4	H & T at 315	9.1	18.0	17.3	16.5	8.6	69.5	
735A51	6150	50CrV4	H & T at 540	6.2	13.6	11.6	11.8	8.6	51.8	
708M40	8650	--	H & T at 205	9.7	19.5	19.4	17.9	8.0	74.4	3
708M40	8650	--	H & T at 315	9.0	18.0	17.3	16.7	8.0	68.9	
708M40	8650	--	H & T at 540	6.1	13.8	11.7	11.6	8.0	51.1	
823M30	**8740**	**30CrNiMo8**	**H & T at 205**	**9.6**	**20.0**	**20.0**	**19.7**	**7.9**	**77.1**	**1**
823M30	8740	30CrNiMo8	H & T at 315	9.0	18.0	17.2	16.9	7.9	68.9	
823M30	8740	30CrNiMo8	H & T at 540	6.6	14.0	12.1	12.5	7.9	53.0	
708M40	4140	42CrMo4	Nitrided	4.4	14.3	10.8	22.3	7.9	59.7	
722M24	--	32CrMo12	Nitrided	4.5	14.3	10.8	27.8	7.2	64.7	
817M40	4340	34CrNiMo6	Nitrided	5.1	15.6	11.8	20.2	6.1	58.8	
897M39	--	--	Nitrided	3.8	11.3	8.5	33.0	6.0	62.6	
905M31	--	--	Nitrided	3.4	11.3	8.6	40.0	5.7	69.0	
905M39	--	41CrAlMo7	Nitrided	4.2	13.6	10.3	31.3	5.5	65.0	

6.5.4 Selection of Low cost shaft steels

6.5.4.1 Relative importance of shaft requirements (Weighting factor)

Cost can be considered as most importance requirement when design select the optimum steel for shaft application.

The cost will be given highest weighting factor by using a digital logic method, as shown in Table (6.12).

Table 6-12 Weighting factors for low cost shaft steels

Determination of relative importance of required properties for Low cost shaft steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	0	0	1	0							1	0.100
Bending Fatigue Strength	1				1			0	0		2	0.200
Shear Fatigue Strength		1			0	1	0				2	0.200
Hardness			0			0		1		0	1	0.100
Cost				1			1		1	1	4	0.400
											10	**1.000**

6.5.4.2 Performance index (γ) for low cost shaft steels

The performance index for candidate steels indicates that (***AISI 5150, DIN 46Cr2***) steel in hardened and tempered at 205 ^{0}C condition is the best choice can be used for low cost shaft steels. Table (6.13) shows the ranking list (Highest 5 ranked steels are red colured) for this application.

Table 6-13 performance index & ranking of Low cost shaft steel

Performance index & Ranking for low cost shaft steels										
Steel Grade Standards			**Condition**	**σy**	**Bending Fatigue strength**	**Shear Fatigue strength**	**Hardness**	**Cost**	**Performance index (γ)**	**Ranking**
BS	**AISI**	**DIN**								
120M19	1022	C22	carburized	2.1	8.3	4.8	2.4	33.3	50.9	
815M17	4320	17CrNiMo6	carburized	2.7	13.7	7.9	3.8	27.8	55.9	
665M20	4620	--	carburized	2.1	9.9	5.8	2.3	28.2	48.3	
--	4820	--	carburized	2.8	13.0	7.5	3.7	23.4	50.5	
805M20	8620	21Ni CrMo2	carburized	3.3	14.8	8.6	3.4	32.9	63.0	
080M40	1040	C40	H & T at 205	3.8	11.4	9.0	4.4	39.4	68.0	
080M40	1040	C40	H & T at 315	3.7	11.4	8.9	3.4	39.4	66.8	
080M40	1040	C40	H & T at 540	3.4	10.4	7.8	2.4	39.4	63.3	
080M50	1050	C50	H & T at 205	4.7	13.4	11.2	4.4	39.4	73.0	
080M50	1050	C50	H & T at 315	4.6	13.1	10.9	3.8	39.4	71.7	
080M50	1050	C50	H & T at 540	3.8	15.8	8.6	2.5	39.4	70.1	
060A62	1060	C60	H & T at 205	4.5	13.2	11.0	2.8	39.4	70.9	
060A62	1060	C60	H & T at 315	4.4	12.9	10.8	2.7	39.4	70.2	
060A62	1060	C60	H & T at 540	3.9	12.0	9.7	2.4	39.4	67.3	
150M36	1340	36Mn5	H & T at 205	9.2	18.6	18.1	4.3	40.0	90.2	2
150M36	1340	36Mn5	H & T at 315	8.2	17.0	15.9	3.9	40.0	84.9	
150M36	1340	36Mn5	H & T at 540	4.8	12.0	9.7	2.6	40.0	69.0	
708A25	4130	25CrMo4	H & T at 205	8.5	17.2	16.1	4.0	35.1	80.8	
708A25	4130	25CrMo4	H & T at 315	8.0	16.4	15.0	3.7	35.1	78.1	
708A25	4130	25CrMo4	H & T at 540	5.3	12.6	10.3	2.7	35.1	66.0	
530M40	5140	41Cr4	H & T at 205	9.5	18.5	17.9	4.2	39.3	89.4	3
530M40	5140	41Cr4	H & T at 315	8.4	16.9	15.1	3.8	39.3	83.5	
530M40	5140	41Cr4	H & T at 540	5.0	12.3	10.0	2.4	39.3	69.0	
--	**5150**	**46Cr2**	**H & T at 205**	**10.0**	**19.6**	**19.5**	**4.5**	**38.0**	**91.6**	**1**
--	5150	46Cr2	H & T at 315	9.3	18.1	17.4	4.1	38.0	86.9	5
--	5150	46Cr2	H & T at 540	6.0	13.4	11.2	2.9	38.0	71.5	
735A51	6150	50CrV4	H & T at 205	9.8	19.5	19.3	4.6	34.5	87.7	4
735A51	6150	50CrV4	H & T at 315	9.1	18.0	17.3	4.1	34.5	83.0	
735A51	6150	50CrV4	H & T at 540	6.2	13.6	11.6	2.9	34.5	68.8	
708M40	8650	--	H & T at 205	9.7	19.5	19.4	4.5	31.8	84.9	
708M40	8650	--	H & T at 315	9.0	18.0	17.3	4.2	31.8	80.2	
708M40	8650	--	H & T at 540	6.1	13.8	11.7	2.9	31.8	66.3	
823M30	8740	30CrNiMo8	H & T at 205	9.6	20.0	20.0	4.9	31.6	86.1	
823M30	8740	30CrNiMo8	H & T at 315	9.0	18.0	17.2	4.2	31.6	79.9	
823M30	8740	30CrNiMo8	H & T at 540	6.6	14.0	12.1	3.1	31.6	67.4	
708M40	4140	42CrMo4	Nitrided	4.4	14.3	10.8	5.6	31.8	66.8	
722M24	--	32CrMo12	Nitrided	4.5	14.3	10.8	7.0	28.8	65.4	
817M40	4340	34CrNiMo6	Nitrided	5.1	15.6	11.8	5.0	24.3	61.9	
897M39	--	--	Nitrided	3.8	11.3	8.5	8.3	24.0	55.8	
905M31	--	--	Nitrided	3.4	11.3	8.6	10.0	22.7	56.0	
905M39	--	41CrAlMo7	Nitrided	4.2	13.6	10.3	7.8	22.1	58.1	

Chapter 7

7 SELECTION OF FASTENERS STEELS

7.1 Introduction

Fasteners come in a wide variety of specifications, but whether you are planning to use a bolt, screw, rivet, peg, or clamp, selecting steels suitable for the intended application is an important concern. For example, choosing a fastener made of carbon steel rather than alloyed steel can greatly affect the quality and duration of the joint it forms. Numerous factors, such as physical stress requirements, mechanical properties of fasteners steel, and others effect structural stability.

Generally, fastener steels are judged on their mechanical properties, potential for post-fabrication treatments, cost-efficiency, and several other secondary criteria.

Carbon steel is the most common type of steel used in fastener production. Grades 2, 5, and 8 are typically the standard for carbon-steel based screws and bolts, with alloyed carbon steel being a higher-end variation on these metals. Their mechanical strength ranges from approximately 345 Mpa up to 2000 Mpa in a finished product [39].

7.2 Fasteners types

The different types of fasteners include screws, nuts, bolts, rivets, retaining rings, pipe plugs, pins, panel fasteners; clinch studs, bolts, and anchors. Fasteners have become a very important in every industry because of the basic but important purpose that they serve. Each component in a machinery or vehicle is dependent upon the fasteners that hold it together. Failure or nonconformity in a fastener can lead to disasters that can be horrendous [40].

7.3 Fasteners steels

There are many different fasteners steels can be compromise such as:

• **Grade 2:** This is a low carbon category that features the least expensive, but also least durable, types of steel. Grade 2 material is highly workable, and forms the bulk of steel grade fasteners.

• **Grade 5:** Grade 5 steels are produced from unalloyed medium carbon groups, such as type 1038, and are usually work-hardened to improve their strength. This is the most common grade used in automotive applications.

• **Grade 8:** These steels are typically medium carbon alloys, such as types 4037 and 4340. They are work-hardened to a high degree, making them stronger and better-suited for mechanically straining applications, like vehicle suspension systems [31].

Alloy Steel: This is an alloy formed with high-strength carbon steel that can be thermally treated up to 2000 Mpa. Alloy steel has low corrosion resistance and typically benefits from additional coating. These steels are extremely strong, but can be rigid and brittle [31].

In steels that are used screws, bolts, nuts, and rivets; cold formability is the main property of use upon which correspondingly high demands are placed.

For large components, good hot formability is also required, depending on manufacturing technique [17].

For certain modes of components manufacture, forming involve machining; for example, when processing the steels into smaller numbers of pieces, or when the mechanical properties of fasteners made of steels must meet high requirements. Consequently, demands are additionally placed on the machinability [4]. Table (7.1) shown steels used for fasteners and their chemical compositions.

Table 7-1 Chemical compositions of Fasteners steel [24], [25], [26] [27

Steel Grade Standards			Chemical Compositions of Fasteners Steels %							
BS	**AISI**	**DIN**	**C**	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mo**
--	1008	UQSt36	max 0.14	0.25-0.50	max 0.050	max 0.050	traces	--	--	--
--	--	USQt38	max 0.19	0.25-0.50	max 0.050	max 0.040	traces	--	--	--
--	--	U7S6	max 0.10	0.30-0.60	max 0.050	0.04-0.08	traces	--	--	--
--	1110	U10S10	max 0.15	0.30-0.60	max 0.050	0.08-0.12	traces	--	--	--
080M15	1015	CK15	0.12-0.18	0.25-0.50	0.035	0.035	0.15-0.35	--	--	--
708H20	4118	20MoCr4	0.17-0.22	0.70-1.00	0.035	0.035	≤0.40	--	0.30-0.60	0.40-0.50
805A17	8617	21NiCrMo2	0.17-0.23	0.65-0.95	0.035	0.035	≤0.40	0.40-0.70	0.40-0.70	0.15-0.25
605A36	4037	--	0.35-0.40	0.70-0.90	0.035	0.04	0.15-0.30	--	--	0.20-0.30
708A30	4137	34CrMo4	0.30-0.37	0.50-0.80	0.035	≤ 0.03	0.15-0.40	--	0.90-1.20	0.15-0.30
--	4042	--	0.40-0.45	0.70-0.90	0.035	0.04	0.15-0.30	--	--	0.20-0.30
708M40	4140	42CrMo4	0.38-0.45	0.50-0.80	0.035	≤ 0.03	0.15-0.40	--	0.90-1.20	0.15-0.30
817M40	4340	34CrNiMo6	0.38-0.43	0.60-0.80	0.035	0.04	0.15-0.35	1.65-2.00	0.70-0.90	0.20-0.30
527M20	5120	16MnCr5	0.14-0.19	1.00-1.30	0.035	0.035	0.15-0.40	--	0.80-1.10	--
530A32	5132	34Cr4	0.30-0.37	0.60-0.90	0.035	≤ 0.03	0.15-0.40	--	0.90-1.20	--
530A36	5135	37Cr4	0.34-0.41	0.60-0.90	0.035	≤ 0.03	0.15-0.40	--	0.90-1.20	--
530M40	5140	41Cr4	0.38-0.45	0.50-0.80	0.035	≤ 0.035	0.15-0.40	--	0.90-1.20	--
823M30	8740	30CrNiMo8	0.26-0.33	0.30-0.60	0.035	≤ 0.03	0.15-0.40	1.80-2.20	1.80-2.20	0.30-0.50

7.4 Mechanical properties required

The required mechanical property value, upon which the design of the fastener is based, must be achieved within tight scatter ranges, with service life being of decisive importance. Screw joints are very sensitive to fatigue failure as a result of the extremely high notch effect of the thread. To improve service life of screw joints, constructional measures should be taken. Where the steels designed for making screws and bolts are concerned [42].

To attain the required mechanical properties in parts manufacturing by cold forming, strain hardening must be taken into account and suitably combined with the other properties being considered. [42]

High-strength screws, bolts and nuts are subjected to heat treatment after forming. The steels therefore must display great uniformity of hardening throughout the cross section of the fastener and must fulfil corresponding hardenability requirements. Screws involving only small deformations (e.g., long-shank screws and long-shank ball pins) increasingly are being made from quenched and tempered wire rod [31].

The case hardening steels used for special screws, bolts, and rivets must be suitable mostly for quenching directly from the carburizing operation and, therefore, must be fine-grained.

Bolts and fasteners are traditionally manufactured from medium carbon steels that sometimes contain alloying elements such as chromium, molybdenum, and nickel. Low carbon micro alloyed steel grads can be used for fasteners [31].

Low carbon unalloyed steels present good cold formability without any special treatment and are therefore particularly well suited for manufacturing screws and bolts in cold condition.

Tables (7.2, 7.3, & 7.4) show the mechanical properties of fasteners steels as hot rolled, carburized, & through hardened conditions respectively [31].

Table 7-2 Mechanical properties of Fasteners steels as Hot Rolled condition [4], [13], [24], [25], [26], [27], [30], [31]

Steel Grade Standards			Mechanical Properties as Hot Rolled treatment							[1]Cost
BS	AISI	DIN	σ_{uts} Mpa	σ_y Mpa	Elong %	[3]Shear Fatigue strength at 107 cycle Mpa	Impact value J	Hardness (HV)	[2]Machinability %	$/kg *$10^{-1}$
--	1008	UQSt36	380	205	30	114	27	108	55	0.420
--	--	USQt38	410	225	25	123	27	110	50	0.420
--	--	U7S6	370	205	25	111	27	108	60	0.450
--	1110	U10S10	405	225	25	122	27	110	55	0.450

[1] Cost is steel prices in 2006 , GRANTA material inspiration , CES EduPack 2006

[2] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

[3] Shear Fatigue is calculated from $\tau_0 = 0.3\ \sigma_{uts}$ [34]

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength (or 0.2% Proof stress)

Table 7-3 Mechanical properties of Fasteners steels as carburized condition[4], [13], [24], [25], [26], [27], [30], [31]

Steel Grade Standards			[1]Mechanical Properties as Carburizing treatment							[2]Cost
BS	AISI	DIN	σ_{uts} Mpa	σ_y Mpa	Elong %	[4]Shear Fatigue strength at 107 cycle , Mpa	Impact value J	Hardness (HV)	[3]Machinability %	$/kg *$10^{-1}$
080M15	1015	CK15	700	440	14	210	69	360	60	0.795
708H20	4118	20MoCr4	930	635	9	279	41	400	50	1.135
805A17	8617	21NiCrMo2	1100	785	9	330	41	410	55	0.972
530A32	5132	34Cr4	1000	700	12	300	35	470	67	0.813
530A36	5135 S4	37Cr4	1050	750	11	315	30	490	60	0.813
527M20	5120 H	16MnCr5	950	635	10	285	34	430	65	0.813

[1] Gas Carburizing at 915 ^{0}C, for 8 hours, 775 ^{0}C reheat, Water quench, 175 ^{0}C temper.

[2] Cost is included row steel price and heat treatment cost (10% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[3] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

[4] Shear Fatigue is calculated from $\tau_0 = 0.3\ \sigma_{uts,}$ [34]

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength (or 0.2% Proof stress)

Table 7-4 Mechanical properties of Fasteners steels as through hardened condition [4], [13], [24], [25], [26], [27], [30], and [31]

Steel Grade Standards			Heat Treatment		Mechanical Properties as Through Hardening Condition							[1]Cost $/kg *$10^{-1}$
BS	AISI	DIN	Quenching ^0C (Medium)	Tempering ^0C	σ_{uts} MPa	σ_y MPa	Elong %	[3]Shear Fatigue strength at 10^7 cycle Mpa	Impact value J	Hardness (HV)	[2]Machinability %	
605A36	4037	--	860 (Oil)	205	1025	760	6	308	24	306	70	0.916
				315	950	765	14	285	26	290		
				540	790	655	23	237	55	245		
708A30	4137	34CrMo4	850 (Oil)	205	1665	1530	13	500	29	500	70	0.933
				315	1500	1460	12	450	19	460		
				540	1060	1010	18	318	52	330		
--	4042	--	845 (Oil)	205	1800	1660	7	540	26	506	65	0.924
				315	1610	1455	13	483	38	445		
				540	980	885	20	294	50	299		
708M40	4140	42CrMo4	845(Oil)	205	1770	1640	8	531	25	500	65	0.929
				315	1550	1430	9	465	30	435		
				540	950	835	18	285	40	280		
817M40	4340	34CrNiMo6	840 (Oil)	205	1823	1675	10	547	20	510	50	1.197
				315	1770	1588	10	531	27	476		
				540	1173	1078	13	352	46	365		
530A32	5132	34Cr4	850 (Oil)	205	1580	1400	2	474	10	480	70	0.951
				315	1480	1320	2	444	5	410		
				540	820	701	15	246	25	255		
530A36	5135	37Cr4	840 (Oil)	205	900	630	13	270	22	280	70	0.960
				315	830	540	17	249	28	258		
				540	740	490	21	222	36	230		
530M40	5140	41Cr4	845 (Oil)	205	1793	1640	9	538	14	481	65	0.813
				315	1508	1448	10	452	16	441		
				540	1000	863	17	300	55	279		
823M30	8740	30CrNiMo8	830 (Oil)	205	2000	1655	10	600	41	566	65	1.013
				315	1718	1550	11	515	45	486		
				540	1208	1138	15	362	47	358		

[1] Cost is included row steel price and heat treatment cost (5% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

[2] Machinability % is measured as annealed condition and based on 100 % machinability for AISI 1212 steel

[3] Shear Fatigue is calculated from $\tau_0 = 0.3\ \sigma_{uts}$, [1] Design Data, Faculty of Mechanical Engineering, PSG College of Technology, Coimbatore.

σ_{uts} is Ultimate tensile strength, σ_y is Yield strength (or 0.2% Proof stress)

7.5 Selection of shaft steels by using weighted property method

For fasteners applications five important properties or requirement are considered, tensile strength, shear fatigue strength, hardness, toughness, and cost, and then scaled by using Eq. (4.1 & 4.2). The scaled value of fasteners steels are given in table (7.5).

Table 7-5 scaled value of fasteners steel properties

Steel Grade Standards			Condition	Scaled values of Fasteners steels				
				Scaled property				
BS	AISI	DIN		σ_{uts}	Shear Fatigue strength	hardness	Toughness	Cost
--	1008	UQSt36	Hot Rolled	12.24	19	19.08	49.09	100
--	--	USQt38	Hot Rolled	13.43	20.5	19.43	49.09	100
--	--	U7S6	Hot Rolled	12.24	18.5	19.08	49.09	93.33
--	1110	U10S10	Hot Rolled	13.43	20.25	19.43	49.09	93.33
080M15	1015	CK15	Carburized	26.27	35	63.6	125.45	52.86
708H20	4118	20MoCr4	Carburized	37.91	46.5	70.67	74.55	37
805A17	8617	21NiCrMo2	Carburized	46.87	55	72.44	74.55	43.21
530A32	5132	34Cr4	Carburized	41.79	50	83.04	63.64	51.64
530A36	5135 S4	37Cr4	Carburized	44.78	52.5	86.57	54.55	51.64
527M20	5120 H	16MnCr5	Carburized	37.91	47.5	75.97	61.82	51.64
605A36	4037	--	H & T at 205	45.37	51.25	54.06	43.64	45.85
605A36	4037	--	H & T at 315	45.67	47.5	51.24	47.27	45.85
605A36	4037	--	H & T at 540	39.1	39.5	43.29	100	45.85
708A30	4137	34CrMo4	H & T at 205	91.34	83.25	88.34	52.73	45.02
708A30	4137	34CrMo4	H & T at 315	87.16	75	81.27	34.55	45.02
708A30	4137	34CrMo4	H & T at 540	60.3	53	58.3	94.55	45.02
--	4042	--	H & T at 205	99.1	90	89.4	47.27	45.45
--	4042	--	H & T at 315	86.87	80.5	78.62	69.09	45.45
--	4042	--	H & T at 540	52.84	49	52.83	90.91	45.45
708M40	4140	42CrMo4	H & T at 205	97.91	88.5	88.34	45.45	45.21
708M40	4140	42CrMo4	H & T at 315	85.37	77.5	76.86	54.55	45.21
708M40	4140	42CrMo4	H & T at 540	49.85	47.5	49.47	72.73	45.21
817M40	4340	34CrNiMo6	H & T at 205	100	91.15	90.11	36.36	35.09
817M40	4340	34CrNiMo6	H & T at 315	94.81	88.5	84.1	49.09	35.09
817M40	4340	34CrNiMo6	H & T at 540	64.36	58.65	64.49	83.64	35.09
530A32	5132	34Cr4	H & T at 205	83.58	79	84.81	18.18	44.16
530A32	5132	34Cr4	H & T at 315	78.81	74	72.44	9.09	44.16
530A32	5132	34Cr4	H & T at 540	41.85	41	45.05	45.45	44.16
530A36	5135	37Cr4	H & T at 205	37.61	45	49.47	40	43.75
530A36	5135	37Cr4	H & T at 315	32.24	41.5	45.58	50.91	43.75
530A36	5135	37Cr4	H & T at 540	29.25	37	40.64	65.45	43.75
530M40	5140	41Cr4	H & T at 205	97.91	89.65	84.98	25.45	51.64
530M40	5140	41Cr4	H & T at 315	86.45	75.4	77.92	29.09	51.64
530M40	5140	41Cr4	H & T at 540	51.52	50	49.29	100	51.64
823M30	8740	30CrNiMo8	H & T at 205	98.81	100	100	74.55	41.46
823M30	8740	30CrNiMo8	H & T at 315	92.54	85.9	85.87	81.82	41.46
823M30	8740	30CrNiMo8	H & T at 540	67.94	60.4	63.25	85.45	41.46
	Highest scaled property value							

7.5.1 Selection of high strength fasteners steels

7.5.1.1 Relative importance of fasteners requirements (Weighting factor)

Five requirements are required for fasteners design, the total number of possible decisions is 10, and the different decisions and weighting factors are given in table (7.6).

Table 7-6 Weighting factors for high strength fasteners steels

Determination of relative importance of required properties for High Strength Fasteners steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	1	1	1	1							4	0.400
Shear Fatigue Strength	0				1	1	0				2	0.200
Hardness		0			0			1	1		2	0.200
Toughness			0			0		0		1	1	0.100
Cost				0			1		0	0	1	0.100
											10	**1.000**

7.5.1.2 Performance index (γ) for high strength fasteners steels

The performance index calculation shows that (***BS 823M30, AISI 8740, DIN 30CrNiMo8)*** steel in hardened and tempered at 205 ^{0}C conditions is the optimum steel can be used for high strength fasteners applications. The ranking list (highest 5 ranked steels are red coloured) of high strength fasteners steels is indicated in table (7.7).

Table 7-7 performance index & ranking of high strength fasteners steels

Performance index & Ranking for High Strength Fasteners steels										
Steel Grade Standards			Condition	σ_Y	Shear Fatigue strength	Hardness	Toughness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
--	1008	UQSt36	Hot Rolled	4.9	3.8	3.8	4.9	10.0	27.4	
--	--	USQt38	Hot Rolled	5.4	4.1	3.9	4.9	10.0	28.3	
--	--	U7S6	Hot Rolled	4.9	7.4	3.8	4.9	9.3	30.4	
--	1110	U10S10	Hot Rolled	5.4	8.1	3.9	4.9	9.3	31.6	
080M15	1015	CK15	Carburized	10.5	14.0	12.7	12.5	5.3	55.1	
708H20	4118	20MoCr4	Carburized	15.2	18.6	14.1	7.5	3.7	59.1	
805A17	8617	21NiCrMo2	Carburized	18.7	22.0	14.5	7.5	4.3	67.0	
530A32	5132	34Cr4	Carburized	16.7	20.0	16.6	6.4	5.2	64.9	
530A36	5135 S4	37Cr4	Carburized	17.9	21.0	17.3	5.5	5.2	66.8	
527M20	5120 H	16MnCr5	Carburized	15.2	19.0	15.2	6.2	5.2	60.7	
605A36	4037	--	H & T at 205	18.1	20.5	10.8	4.4	4.6	58.4	
605A36	4037	--	H & T at 315	18.3	19.0	10.2	4.7	4.6	56.8	
605A36	4037	--	H & T at 540	15.6	15.8	8.7	10.0	4.6	54.7	
708A30	4137	34CrMo4	H & T at 205	36.5	33.3	17.7	5.3	4.5	97.3	
708A30	4137	34CrMo4	H & T at 315	34.9	30.0	16.3	3.5	4.5	89.1	
708A30	4137	34CrMo4	H & T at 540	24.1	21.2	11.7	9.5	4.5	70.9	
--	4042	--	H & T at 205	39.6	36.0	17.9	4.7	4.5	102.8	2
--	4042	--	H & T at 315	34.7	32.2	15.7	6.9	4.5	94.1	
--	4042	--	H & T at 540	21.1	19.6	10.6	9.1	4.5	64.9	
708M40	4140	42CrMo4	H & T at 205	39.2	35.4	17.7	4.5	4.5	101.3	
708M40	4140	42CrMo4	H & T at 315	34.1	31.0	15.4	5.5	4.5	90.5	
708M40	4140	42CrMo4	H & T at 540	19.9	19.0	9.9	7.3	4.5	60.6	
817M40	4340	34CrNiMo6	H & T at 205	40.0	36.5	18.0	3.6	3.5	101.6	3
817M40	4340	34CrNiMo6	H & T at 315	37.9	35.4	16.8	4.9	3.5	98.6	
817M40	4340	34CrNiMo6	H & T at 540	25.7	23.5	12.9	8.4	3.5	74.0	
530A32	5132	34Cr4	H & T at 205	33.4	31.6	17.0	1.8	4.4	88.2	
530A32	5132	34Cr4	H & T at 315	31.5	29.6	14.5	0.9	4.4	80.9	
530A32	5132	34Cr4	H & T at 540	16.7	16.4	9.0	4.5	4.4	51.1	
530A36	5135	37Cr4	H & T at 205	15.0	18.0	9.9	4.0	4.4	51.3	
530A36	5135	37Cr4	H & T at 315	12.9	16.6	9.1	5.1	4.4	48.1	
530A36	5135	37Cr4	H & T at 540	11.7	14.8	8.1	6.5	4.4	45.5	
530M40	5140	41Cr4	H & T at 205	39.2	35.9	17.0	2.5	5.2	99.7	5
530M40	5140	41Cr4	H & T at 315	34.6	30.2	15.6	2.9	5.2	88.4	
530M40	5140	41Cr4	H & T at 540	20.6	20.0	9.9	10.0	5.2	65.6	
823M30	**8740**	**30CrNiMo8**	**H & T at 205**	**39.5**	**40.0**	**20.0**	**7.5**	**4.1**	**111.1**	**1**
823M30	8740	30CrNiMo8	H & T at 315	37.0	34.4	17.2	8.2	4.1	100.9	4
823M30	8740	30CrNiMo8	H & T at 540	27.2	24.2	12.7	8.5	4.1	76.7	

7.5.2 Selection of high fatigue strength fasteners steels

7.5.2.1 Relative importance of fasteners requirements (Weighting factor)

By using a digital logic method a weighing factor (α) for each property will be determined as shown in Table (7.8).

Table 7-8 Weighting factors for shear fatigue strength fasteners steels

Determination of relative importance of required properties for High Fatigue Strength of Fasteners steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	0	1	0	1							2	0.200
Shear Fatigue Strength	1				1	1	1				4	0.400
Hardness		0			0			1	0		1	0.100
Toughness			1			0		0		1	2	0.200
Cost				0			0		1	0	1	0.100
											10	**1.000**

7.5.2.2 Performance index (γ) for high strength fasteners steels

The ranking list for high shear fatigue fasteners steel (highest 5 ranked steels are red colured) is shown in table (7.9), and from the table its obvious that steel ***(BS 823M30, AISI 8740, DIN*** **30CrNiMo8) is the best choice for this application in** hardened and tempered at 205 ^{0}C condition.

Table 7-9 performance index & ranking of high strength fasteners steels

Performance index & Ranking for High Fatigue Fasteners steels										
Steel Grade Standards			Condition	σ_Y	Shear Fatigue strength	Hardness	Toughness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
--	1008	UQSt36	Hot Rolled	2.4	7.6	1.9	9.8	10.0	**31.8**	
--	--	USQt38	Hot Rolled	2.7	8.2	1.9	9.8	10.0	**32.6**	
--	--	U7S6	Hot Rolled	2.4	3.7	1.9	9.8	9.3	**27.2**	
--	1110	U10S10	Hot Rolled	2.7	4.1	1.9	9.8	9.3	**27.8**	
080M15	1015	CK15	Carburized	5.3	7.0	6.4	25.1	5.3	**49.0**	
708H20	4118	20MoCr4	Carburized	7.6	9.3	7.1	14.9	3.7	**42.6**	
805A17	8617	21NiCrMo2	Carburized	9.4	11.0	7.2	14.9	4.3	**46.8**	
530A32	5132	34Cr4	Carburized	8.4	10.0	8.3	12.7	5.2	**44.6**	
530A36	5135 S4	37Cr4	Carburized	9.0	10.5	8.7	10.9	5.2	**44.2**	
527M20	5120 H	16MnCr5	Carburized	7.6	9.5	7.6	12.4	5.2	**42.2**	
605A36	4037	--	H & T at 205	9.1	10.3	5.4	8.7	4.6	**38.0**	
605A36	4037	--	H & T at 315	9.1	9.5	5.1	9.5	4.6	**37.8**	
605A36	4037	--	H & T at 540	7.8	7.9	4.3	20.0	4.6	**44.6**	
708A30	**4137**	**34CrMo4**	**H & T at 205**	**18.3**	**16.7**	**8.8**	**10.5**	**4.5**	**58.8**	**5**
708A30	4137	34CrMo4	H & T at 315	17.4	15.0	8.1	6.9	4.5	**52.0**	
708A30	4137	34CrMo4	H & T at 540	12.1	10.6	5.8	18.9	4.5	**51.9**	
--	**4042**	**--**	**H & T at 205**	**19.8**	**18.0**	**8.9**	**9.5**	**4.5**	**60.8**	**3**
--	**4042**	**--**	**H & T at 315**	**17.4**	**16.1**	**7.9**	**13.8**	**4.5**	**59.7**	**4**
--	4042	--	H & T at 540	10.6	9.8	5.3	18.2	4.5	**48.4**	
708M40	**4140**	**42CrMo4**	**H & T at 205**	**19.6**	**17.7**	**8.8**	**9.1**	**4.5**	**59.7**	**4**
708M40	4140	42CrMo4	H & T at 315	17.1	15.5	7.7	10.9	4.5	**55.7**	
708M40	4140	42CrMo4	H & T at 540	10.0	9.5	4.9	14.5	4.5	**43.5**	
817M40	4340	34CrNiMo6	H & T at 205	20.0	18.2	9.0	7.3	3.5	**58.0**	
817M40	4340	34CrNiMo6	H & T at 315	19.0	17.7	8.4	9.8	3.5	**58.4**	
817M40	4340	34CrNiMo6	H & T at 540	12.9	11.7	6.4	16.7	3.5	**51.3**	
530A32	5132	34Cr4	H & T at 205	16.7	15.8	8.5	3.6	4.4	**49.0**	
530A32	5132	34Cr4	H & T at 315	15.8	14.8	7.2	1.8	4.4	**44.0**	
530A32	5132	34Cr4	H & T at 540	8.4	8.2	4.5	9.1	4.4	**34.6**	
530A36	5135	37Cr4	H & T at 205	7.5	9.0	4.9	8.0	4.4	**33.8**	
530A36	5135	37Cr4	H & T at 315	6.4	8.3	4.6	10.2	4.4	**33.9**	
530A36	5135	37Cr4	H & T at 540	5.9	7.4	4.1	13.1	4.4	**34.8**	
530M40	**5140**	**41Cr4**	**H & T at 205**	**19.6**	**17.9**	**8.5**	**5.1**	**5.2**	**56.3**	**5**
530M40	5140	41Cr4	H & T at 315	17.3	15.1	7.8	5.8	5.2	**51.1**	
530M40	5140	41Cr4	H & T at 540	10.3	10.0	4.9	20.0	5.2	**50.4**	
823M30	**8740**	**30CrNiMo8**	**H & T at 205**	**19.8**	**20.0**	**10.0**	**14.9**	**4.1**	**68.8**	**1**
823M30	**8740**	**30CrNiMo8**	**H & T at 315**	**18.5**	**17.2**	**8.6**	**16.4**	**4.1**	**64.8**	**2**
823M30	8740	30CrNiMo8	H & T at 540	13.6	12.1	6.3	17.1	4.1	**53.2**	

7.5.3 Selection of high hardness fasteners steels

7.5.3.1 Relative importance of fasteners requirements (Weighting factor)

In this application high hardness will be the most important requirement for fasteners, the weighing factors (α) is calculated by using a digital logic method and they are shown in Table (7.10).

Table 7-10 Weighting factors for high hardness fasteners steels

Determination of relative importance of required properties for High Hardness of Fasteners steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	0	0	1	1							2	0.200
Shear Fatigue Strength	1				0	1	0				2	0.200
Hardness		1			1			1	1		4	0.400
Toughness			0			0		0		1	1	0.100
Cost				0			1		0	0	1	0.100
											10	**1.000**

7.5.3.2 Performance index (γ) for high hardness fasteners steels

Table (7.11) shows the best steel can be used for high hardness fasteners application is ***(BS 823M30, AISI 8740, DIN 30CrNiMo8***) steel in the hardened and tempered at 205 ^{0}C condition.

Table 7-11 performance index & ranking of high strength fasteners steels

Performance index & Ranking for High Hardness Fasteners steels										
Steel Grade Standards			Condition	σ_Y	Shear Fatigue strength	Hardness	Toughness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
--	1008	UQSt36	Hot Rolled	2.4	3.8	7.6	4.9	10	**28.8**	
--	--	USQt38	Hot Rolled	2.7	4.1	7.8	4.9	10	**29.5**	
--	--	U7S6	Hot Rolled	2.4	3.7	7.6	4.9	9.3	**28**	
--	1110	U10S10	Hot Rolled	2.7	4.1	7.8	4.9	9.3	**28.8**	
080M15	1015	CK15	Carburized	5.3	7	25.4	12.5	5.3	**55.5**	
708H20	4118	20MoCr4	Carburized	7.6	9.3	28.3	7.5	3.7	**56.3**	
805A17	8617	21NiCrMo2	Carburized	9.4	11	29	7.5	4.3	**61.1**	
530A32	5132	34Cr4	Carburized	8.4	10	33.2	6.4	5.2	**63.1**	
530A36	5135 S4	37Cr4	Carburized	9	10.5	34.6	5.5	5.2	**64.7**	
527M20	5120 H	16MnCr5	Carburized	7.6	9.5	30.4	6.2	5.2	**58.8**	
605A36	4037	--	H & T at 205	9.1	10.3	21.6	4.4	4.6	**49.9**	
605A36	4037	--	H & T at 315	9.1	9.5	20.5	4.7	4.6	**48.4**	
605A36	4037	--	H & T at 540	7.8	7.9	17.3	10	4.6	**47.6**	
708A30	4137	34CrMo4	H & T at 205	18.3	16.7	35.3	5.3	4.5	**80**	
708A30	4137	34CrMo4	H & T at 315	17.4	15	32.5	3.5	4.5	**72.9**	
708A30	4137	34CrMo4	H & T at 540	12.1	10.6	23.3	9.5	4.5	**59.9**	
--	4042	--	H & T at 205	19.8	18	35.8	4.7	4.5	**82.9**	**2**
--	4042	--	H & T at 315	17.4	16.1	31.4	6.9	4.5	**76.4**	
--	4042	--	H & T at 540	10.6	9.8	21.1	9.1	4.5	**55.1**	
708M40	4140	42CrMo4	H & T at 205	19.6	17.7	35.3	4.5	4.5	**81.7**	
708M40	4140	42CrMo4	H & T at 315	17.1	15.5	30.7	5.5	4.5	**73.3**	
708M40	4140	42CrMo4	H & T at 540	10	9.5	19.8	7.3	4.5	**51.1**	
817M40	4340	34CrNiMo6	H & T at 205	20	18.2	36	3.6	3.5	**81.4**	**3**
817M40	4340	34CrNiMo6	H & T at 315	19	17.7	33.6	4.9	3.5	**78.7**	
817M40	4340	34CrNiMo6	H & T at 540	12.9	11.7	25.8	8.4	3.5	**62.3**	
530A32	5132	34Cr4	H & T at 205	16.7	15.8	33.9	1.8	4.4	**72.7**	
530A32	5132	34Cr4	H & T at 315	15.8	14.8	29	0.9	4.4	**64.9**	
530A32	5132	34Cr4	H & T at 540	8.4	8.2	18	4.5	4.4	**43.6**	
530A36	5135	37Cr4	H & T at 205	7.5	9	19.8	4	4.4	**44.7**	
530A36	5135	37Cr4	H & T at 315	6.4	8.3	18.2	5.1	4.4	**42.4**	
530A36	5135	37Cr4	H & T at 540	5.9	7.4	16.3	6.5	4.4	**40.4**	
530M40	5140	41Cr4	H & T at 205	19.6	17.9	34	2.5	5.2	**79.2**	**5**
530M40	5140	41Cr4	H & T at 315	17.3	15.1	31.2	2.9	5.2	**71.6**	
530M40	5140	41Cr4	H & T at 540	10.3	10	19.7	10	5.2	**55.2**	
823M30	**8740**	**30CrNiMo8**	**H & T at 205**	**19.8**	**20**	**40**	**7.5**	**4.1**	**91.4**	**1**
823M30	8740	30CrNiMo8	H & T at 315	18.5	17.2	34.3	8.2	4.1	**82.4**	**4**
823M30	8740	30CrNiMo8	H & T at 540	13.6	12.1	25.3	8.5	4.1	**63.7**	

7.5.4 Selection of high toughness fasteners steels

7.5.4.1 Relative importance of fasteners requirements (Weighting factor)

Toughness will be considered as the most important property for gear requirements, and the weighing factors (α) for other requirements will determined by using a digital logic as shown in Table (7.12).

Table 7-12 Weighting factors for high toughness fasteners steels

Determination of relative importance of required properties for High toughness of Fasteners steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	1	1	0	0							2	0.200
Shear Fatigue Strength	0				1	0	1				2	0.200
Hardness		0			0			0	1		1	0.100
Toughness			1			1		1		1	4	0.400
Cost				1			0		0	0	1	0.100
											10	**1.000**

7.5.4.2 Performance index (γ) for high toughness fasteners steels

Performance index calculations are shown the best steel can be used for high toughness fasteners applications is **(BS 823M30, AISI 8740, DIN 30CrNiMo8)** hardened and tempered at 205 ^{0}C condition.

The ranking list for high toughness fasteners steels (highest 5 ranked steels are red colured) is shown in Table (7.13).

Table 7-13 performance index & ranking of high toughness fasteners steels

Performance index & Ranking for High Strength Fasteners steels											
Steel Grade Standards			Condition	σ_Y	Shear Fatigue strength	Hardness	Toughness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
--	1008	UQSt36	Hot Rolled	2.4	3.8	1.9	19.6	10.0	**37.8**	
--	--	USQt38	Hot Rolled	2.7	4.1	1.9	19.6	10.0	**38.4**	
--	--	U7S6	Hot Rolled	2.4	3.7	1.9	19.6	9.3	**37.0**	
--	1110	U10S10	Hot Rolled	2.7	4.1	1.9	19.6	9.3	**37.6**	
080M15	1015	CK15	Carburized	5.3	7.0	6.4	50.2	5.3	**74.1**	
708H20	4118	20MoCr4	Carburized	7.6	9.3	7.1	29.8	3.7	**57.5**	
805A17	8617	21NiCrMo2	Carburized	9.4	11.0	7.2	29.8	4.3	**61.8**	
530A32	5132	34Cr4	Carburized	8.4	10.0	8.3	25.5	5.2	**57.3**	
530A36	5135 S4	37Cr4	Carburized	9.0	10.5	8.7	21.8	5.2	**55.1**	
527M20	5120 H	16MnCr5	Carburized	7.6	9.5	7.6	24.7	5.2	**54.6**	
605A36	4037	--	H & T at 205	9.1	10.3	5.4	17.5	4.6	**46.8**	
605A36	4037	--	H & T at 315	9.1	9.5	5.1	18.9	4.6	**47.3**	
605A36	4037	--	H & T at 540	7.8	7.9	4.3	40.0	4.6	**64.6**	
708A30	4137	34CrMo4	H & T at 205	18.3	16.7	8.8	21.1	4.5	**69.3**	
708A30	4137	34CrMo4	H & T at 315	17.4	15.0	8.1	13.8	4.5	**58.9**	
708A30	**4137**	**34CrMo4**	**H & T at 540**	**12.1**	**10.6**	**5.8**	**37.8**	**4.5**	**70.8**	**4**
--	4042	--	H & T at 205	19.8	18.0	8.9	18.9	4.5	**70.2**	
--	**4042**	**--**	**H & T at 315**	**17.4**	**16.1**	**7.9**	**27.6**	**4.5**	**73.5**	**3**
--	4042	--	H & T at 540	10.6	9.8	5.3	36.4	4.5	**66.6**	
708M40	4140	42CrMo4	H & T at 205	19.6	17.7	8.8	18.2	4.5	**68.8**	
708M40	4140	42CrMo4	H & T at 315	17.1	15.5	7.7	21.8	4.5	**66.6**	
708M40	4140	42CrMo4	H & T at 540	10.0	9.5	4.9	29.1	4.5	**58.0**	
817M40	4340	34CrNiMo6	H & T at 205	20.0	18.2	9.0	14.5	3.5	**65.3**	
817M40	4340	34CrNiMo6	H & T at 315	19.0	17.7	8.4	19.6	3.5	**68.2**	
817M40	4340	34CrNiMo6	H & T at 540	12.9	11.7	6.4	33.5	3.5	**68.0**	
530A32	5132	34Cr4	H & T at 205	16.7	15.8	8.5	7.3	4.4	**52.7**	
530A32	5132	34Cr4	H & T at 315	15.8	14.8	7.2	3.6	4.4	**45.9**	
530A32	5132	34Cr4	H & T at 540	8.4	8.2	4.5	18.2	4.4	**43.7**	
530A36	5135	37Cr4	H & T at 205	7.5	9.0	4.9	16.0	4.4	**41.8**	
530A36	5135	37Cr4	H & T at 315	6.4	8.3	4.6	20.4	4.4	**44.0**	
530A36	5135	37Cr4	H & T at 540	5.9	7.4	4.1	26.2	4.4	**47.9**	
530M40	5140	41Cr4	H & T at 205	19.6	17.9	8.5	10.2	5.2	**61.4**	
530M40	5140	41Cr4	H & T at 315	17.3	15.1	7.8	11.6	5.2	**57.0**	
530M40	**5140**	**41Cr4**	**H & T at 540**	**10.3**	**10.0**	**4.9**	**40.0**	**5.2**	**70.4**	**5**
823M30	**8740**	**30CrNiMo8**	**H & T at 205**	**19.8**	**20.0**	**10.0**	**29.8**	**4.1**	**83.7**	**1**
823M30	**8740**	**30CrNiMo8**	**H & T at 315**	**18.5**	**17.2**	**8.6**	**32.7**	**4.1**	**81.1**	**2**
823M30	8740	30CrNiMo8	H & T at 540	13.6	12.1	6.3	34.2	4.1	**70.3**	

7.5.5 Selection of low cost fasteners steels

7.5.5.1 Relative importance of fasteners requirements (Weighting factor)

The cost will be considered as the most important property for fasteners requirements as shown in table (7.14).

Table 7-14 Weighting factors for low cost fasteners steels

Determination of relative importance of required properties for Low cost of Fasteners steels by using the digital logic method												
Required property (n)	**Number of possible decisions (N)**										**Positive decision (m)**	**Weighting factor (α)**
	1	2	3	4	5	6	7	8	9	10		
Yield strength	1	1	0	0							2	0.200
Shear Fatigue Strength	0				1	1	0				2	0.200
Hardness		0			0			1	0		1	0.100
Toughness			1			0		0		0	1	0.100
Cost				1			1		1	1	4	0.400
											10	**1.000**

7.5.5.2 Performance index (γ) for low cost fasteners steels

Performance index calculations are shown that the optimum steel can be used when the cost is first requirement for fasteners design is (BS 823M30, 8740 AISI, 30CrNiMo8 DIN) steel in hardened and tempered at 205 ^{0}C condition.

The ranking list for low cost fasteners steels (highest 5 ranked steels are red colured) is shown in table (7.15).

Table 7-15 performance index & ranking of low cost fasteners steels

Performance index & Ranking for Low cost Fasteners steels											
Steel Grade Standards			Condition	σ_Y	Shear Fatigue strength	Hardness	Toughness	Cost	Performance index (γ)	Ranking
BS	AISI	DIN								
--	1008	UQSt36	Hot Rolled	2.4	3.8	1.9	4.9	40.0	**53.1**	
--	--	USQt38	Hot Rolled	2.7	4.1	1.9	4.9	40.0	**53.6**	
--	--	U7S6	Hot Rolled	2.4	3.7	1.9	4.9	37.3	**50.3**	
--	1110	U10S10	Hot Rolled	2.7	4.1	1.9	4.9	37.3	**50.9**	
080M15	1015	CK15	Carburized	5.3	7.0	6.4	12.5	21.1	**52.3**	
708H20	4118	20MoCr4	Carburized	7.6	9.3	7.1	7.5	14.8	**46.2**	
805A17	8617	21NiCrMo2	Carburized	9.4	11.0	7.2	7.5	17.3	**52.4**	
530A32	5132	34Cr4	Carburized	8.4	10.0	8.3	6.4	20.7	**53.7**	
530A36	5135 S4	37Cr4	Carburized	9.0	10.5	8.7	5.5	20.7	**54.2**	
527M20	5120 H	16MnCr5	Carburized	7.6	9.5	7.6	6.2	20.7	**51.5**	
605A36	4037	--	H & T at 205	9.1	10.3	5.4	4.4	18.3	**47.4**	
605A36	4037	--	H & T at 315	9.1	9.5	5.1	4.7	18.3	**46.8**	
605A36	4037	--	H & T at 540	7.8	7.9	4.3	10.0	18.3	**48.4**	
708A30	4137	34CrMo4	H & T at 205	18.3	16.7	8.8	5.3	18.0	**67.0**	
708A30	4137	34CrMo4	H & T at 315	17.4	15.0	8.1	3.5	18.0	**62.0**	
708A30	4137	34CrMo4	H & T at 540	12.1	10.6	5.8	9.5	18.0	**56.0**	
--	**4042**	**--**	**H & T at 205**	**19.8**	**18.0**	**8.9**	**4.7**	**18.2**	**69.7**	**2**
--	4042	--	H & T at 315	17.4	16.1	7.9	6.9	18.2	**66.4**	
--	4042	--	H & T at 540	10.6	9.8	5.3	9.1	18.2	**52.9**	
708M40	**4140**	**42CrMo4**	**H & T at 205**	**19.6**	**17.7**	**8.8**	**4.5**	**18.1**	**68.7**	**5**
708M40	4140	42CrMo4	H & T at 315	17.1	15.5	7.7	5.5	18.1	**63.8**	
708M40	4140	42CrMo4	H & T at 540	10.0	9.5	4.9	7.3	18.1	**49.8**	
817M40	4340	34CrNiMo6	H & T at 205	20.0	18.2	9.0	3.6	14.0	**64.9**	
817M40	4340	34CrNiMo6	H & T at 315	19.0	17.7	8.4	4.9	14.0	**64.0**	
817M40	4340	34CrNiMo6	H & T at 540	12.9	11.7	6.4	8.4	14.0	**53.4**	
530A32	5132	34Cr4	H & T at 205	16.7	15.8	8.5	1.8	17.7	**60.5**	
530A32	5132	34Cr4	H & T at 315	15.8	14.8	7.2	0.9	17.7	**56.4**	
530A32	5132	34Cr4	H & T at 540	8.4	8.2	4.5	4.5	17.7	**43.3**	
530A36	5135	37Cr4	H & T at 205	7.5	9.0	4.9	4.0	17.5	**43.0**	
530A36	5135	37Cr4	H & T at 315	6.4	8.3	4.6	5.1	17.5	**41.9**	
530A36	5135	37Cr4	H & T at 540	5.9	7.4	4.1	6.5	17.5	**41.4**	
530M40	**5140**	**41Cr4**	**H & T at 205**	**19.6**	**17.9**	**8.5**	**2.5**	**20.7**	**69.2**	**3**
530M40	5140	41Cr4	H & T at 315	17.3	15.1	7.8	2.9	20.7	**63.7**	
530M40	5140	41Cr4	H & T at 540	10.3	10.0	4.9	10.0	20.7	**55.9**	
823M30	**8740**	**30CrNiMo8**	**H & T at 205**	**19.8**	**20.0**	**10.0**	**7.5**	**16.6**	**73.8**	**1**
823M30	**8740**	**30CrNiMo8**	**H & T at 315**	**18.5**	**17.2**	**8.6**	**8.2**	**16.6**	**69.0**	**4**
823M30	8740	30CrNiMo8	H & T at 540	13.6	12.1	6.3	8.5	16.6	**57.1**	

Chapter 8

8 SELECTION OF SPRINGS STEELS

8.1 Definition

Springs are elastic members that expert forces, or torques, and absorb energy, which is usually stored and later released [43]. Energy is stored in the solid that is bent, twisted, stretched, or compressed to form the spring. The energy is recoverable by the elastic return of the distorted material. Springs must have the ability to withstand large deflections elastically. The force can be a linear push or pull, or it can be radial. The torque can be used to cause rotation or to provide a counterbalance force for a machine element pivoting on hinge. Springs frequently operate with high working stresses and with loads that are continuously varying [39].

Springs are usually required to perform the following functions:

- To apply force and to control motion by maintaining contact between two elements, namely cam and follower, governor, I.C. engine valve.
- To cushion, absorb, or control energy due to shock and veneration, e.g. automobile springs aircraft landing gears, railway buffers, and vibration dampers.
- To measure force, e.g. springs balance, meters, and engine indictor.
- To store energy, e.g. clocks, toys, circuits breakers, and starters.
- To alter the vibration characteristics of a member, e.g. the flexible mountings of a motor [39].

8.2 Types of springs

Springs can be classified according to their shape and the type of stresses they have to withstand. On the basis of shape, springs may be classified as wire spring, flat spring, and special-shape spring such as disc spring [14].

The most common types of springs are:

8.2.1 Helical spring

Cylindrical springs having a certain helix angle, usually about 10^0, are called helical springs. These springs may sustain tensile, compressive, or tensional force along their axes. Accordingly, they are called extension, compression, or tensional helical springs. Helical springs are made of circular, rectangular section or square section wire. Theses springs are available in a wide range and are easy to manufacture, figure (8.1, 8.2, & 8.3) [41].

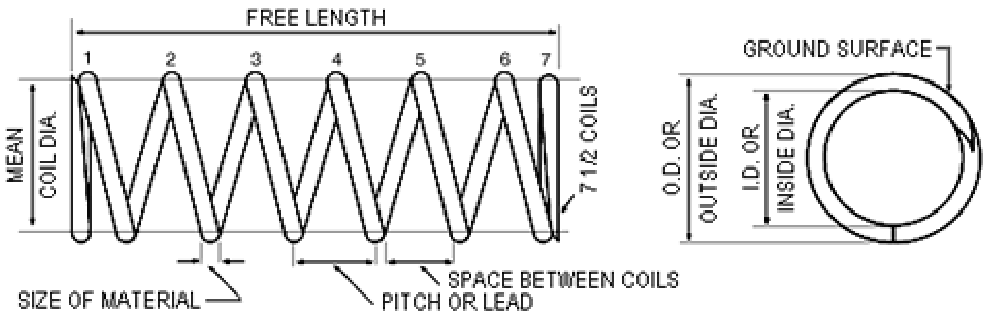


Figure 8-1 Compression helical spring

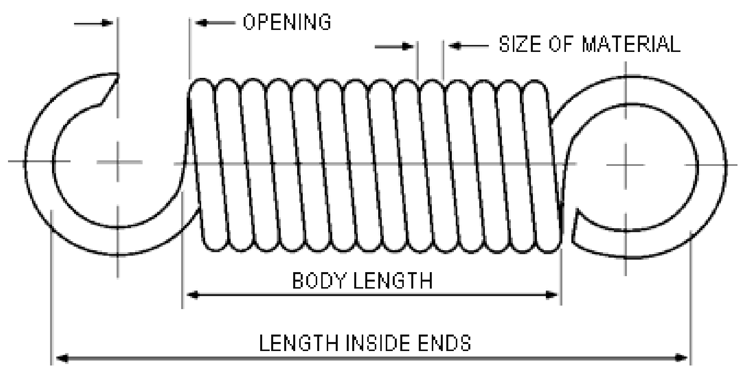


Figure 8-2 Extension helical spring [42]

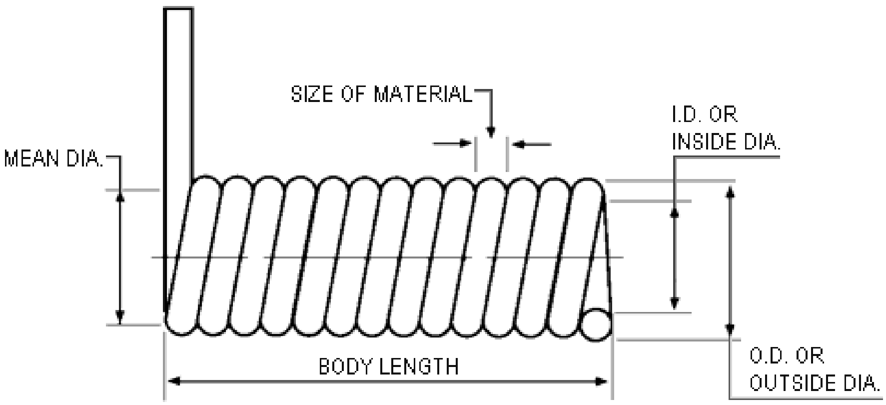


Figure 8-3 Tensional helical spring [42]

8.2.2 Conical springs

A conical spring works in compression. It is made of round wire in the shape of cone, figure (8.4). It is used either where space limitation does not allow using cylindrical helical spring or where a variable rate of stiffness is desired with a single spring [4].

8.2.3 Leaf spring

A leaf spring comprises a flat plate supported at both ends, thus acting as a double cantilever. The major stresses are tensile or compressive. These types of springs may have more than on plate and in that case they are called laminated leaf springs, a leaf spring may be of full-elliptical, semi-elliptical, or cantilever type, figure (8.5) [41].

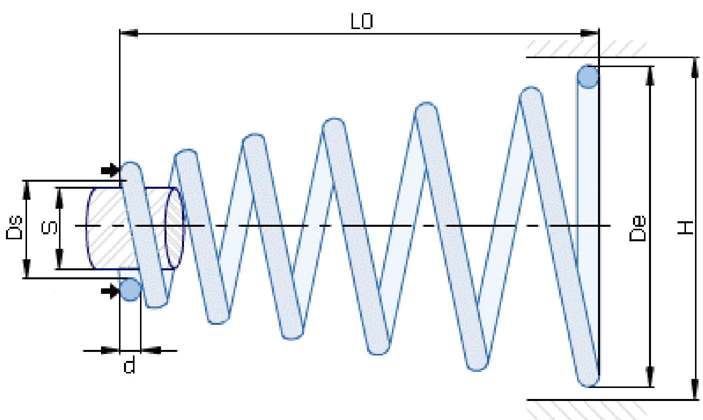


Figure 8-4 conical spring [42]

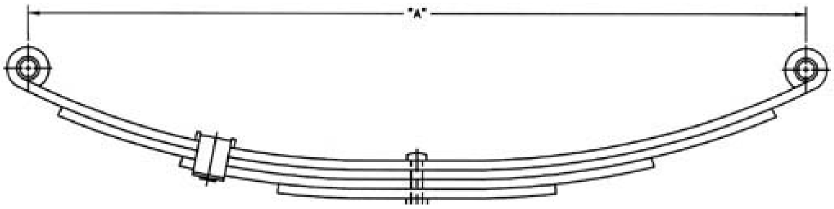


Figure 8-5 laminated leaf spring [42]

8.2.4 Spiral spring

A flat spring of rectangular cross-section when wound in the form of a spiral i.e. with zero helix angle, results in a spiral spring as shown in figure (8.6). These springs are loaded in tension. Major stresses developed in such springs are tensile and compressive in nature due to bending [41].

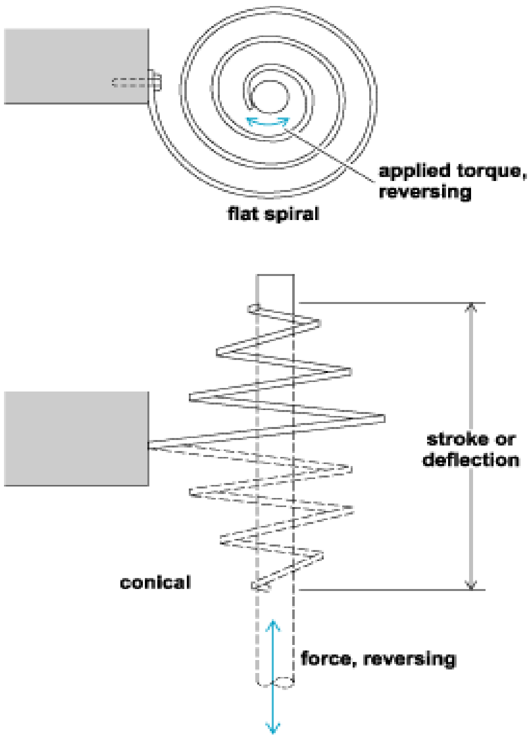


Figure 8-6 Spiral spring [42]

8.2.5 Disc spring

These springs are also known as Belleville springs. They are made in the form of a cone disc to carry a high compressive force. In order to improve their load carrying capacity, they may be stacked up together. The major stresses ate either tensile or compressive figure (8.7) [41].

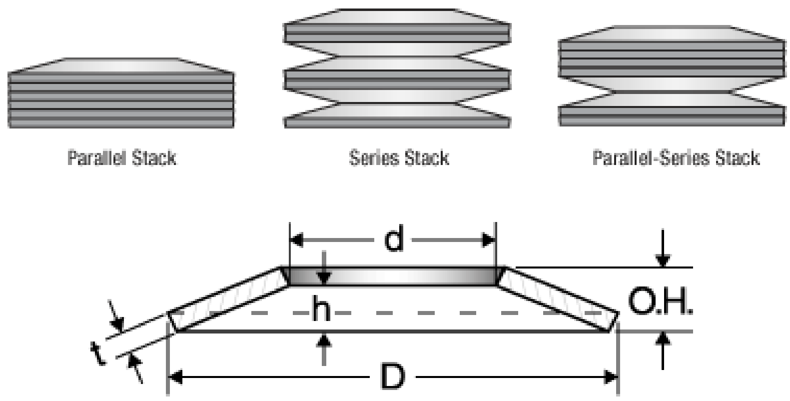


Figure 8-7 Disc (Belleville) spring

8.3 Steels for springs

Depending on the type of application, springs are made of carbon steels, silicon and manganese containing steels, silicon-manganese steels.

Springs must be retaining their original shape and dimension. This property may be attained by use of a highly elastic steels and buy proper design because of allowable stress values determine the choice of steels and design.

Theses desirable properties of sprigs can be achieved firstly by a higher carbon content or with suitable alloying elements, and secondly by heat treatment [31].

Steels springs are used in hard and high strength condition. To attain these properties springs are hardened and tempered. In the hardened condition, the steel should have 100% Martensite to attain the maximum yield strength to avoid excessive set in service.

The presence of retained austenite in the hardened condition lowers the yield strength and produces excessive set [13].

For many applications, where the working stresses are low, carbon springs steels are quite satisfactory for smaller cross-sections. But, for higher cross-sections or high duty springs, steels of higher hardenability are used.

Springs steels are commercially available are carbon spring steel, silico-manganse steel, manganese alloyed steel, silicon alloyed steel, chrome-vanadium steel, etc [13], and table (8.1) shows the chemical composition for spring steels.

Springs of small dimensions are also usually made from patented drawn spring wires coiled in the cold state. They possess a very high tensile strength and elastic properties compared to the normally drown wire. They also possess good ductility and toughness [31].

Table 8-1 Chemical composition for spring steels [24], [25], [26] [27]

Steel Grade Standards			% Chemical Compositions of Spring Steels								
BS	**AISI**	**DIN**	**C**	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mo**	**Others**
060A62	1060	C60	0.55-0.65	0.60-0.90	0.04	0.05	--	--	--	--	--
080A83	1080	--	0.74-0.88	0.60-0.90	0.04	0.05	--	--	--	--	--
060A96	1095	CK101	0.90-1.03	0.30-0.50	0.04	0.05	--	--	--	--	--
216M44	1144	--	0.40-0.48	1.35-1.65	0.04	0.24-0.33					
150M36	1340	36Mn5	0.38-0.43	1.60-1.90	0.035	0.04	0.15-0.35	--	--	--	--
708M40	4150	50CrMo4	0.48-0.53	0.75-1.00	0.035	0.04	0.15-0.35	--	0.80-1.10	0.15-0.25	
--	5150	46Cr2	0.48-0.53	0.70-0.90	0.035	0.04	0.15-0.30	--	0.70-0.90	--	--
527H60	5160	--	0.56-0.64	0.75-1.00	0.035	0.04	0.15-0.30	--	0.70-0.90	--	--
735A51	6150	50CrV4	0.48-0.53	0.70-0.90	0.035	0.04	0.15-0.30	--	0.80-1.10	--	V 0.15 min.
708M40	8650	--	0.48-0.53	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25	--
805A60	8660	--	0.56-0.64	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25	--
251A58	9255	--	0.51-0.59	0.70-0.95	0.035	0.04	1.80-2.20	--	--	--	--
251A60	9260	--	0.56-0.64	0.75-1.00	0.035	0.04	1.80-2.20	--	--	--	--
--	50B60	--	0.56-0.64	0.75-1.00	0.035	0.04	0.15-0.30	--	--	--	0.0005-0.003
--	51B60	--	0.56-0.64	0.70-0.90	0.035	0.04	0.15-0.30	--	--	--	0.0005-0.003
--	86B45	--	0.43-0.48	0.75-1.00	0.035	0.04	0.15-0.30	0.40-0.70	--	0.15-0.25	0.0005-0.003

8.3.1 Steels for cold formed springs (Patenting)

Unalloyed steels are employed largely for cold formed springs.

Springs for lower stresses or unspecified qualifications are made of wires drawn from wire rod or of cold rolled strip with carbon content from 0.05% to 0.50%. In selecting the steel it must be considered that the hardness of the hot rolled products influences greatly the processing by drawing and cold rolling as well as by cold coiling of the springs. A sufficient degree of deformability after drawing or cold rolling must be maintained for the subsequent shaping of the spring. To increase limit of elasticity, a short-term tempering of the springs at 200 ^{0}C to 300 ^{0}C is useful [42].

Unalloyed steels containing 0.40% to 1% C, mainly as patented and drawn or drawn and quenched, and tempered wires, are used for cold formed springs. Thus steels with 0.6% to 0.7% C are used in the quenched and tempered condition for cold formed valve springs. Also roll springs and coiled springs as well as highly stressed engine springs are made from cold rolled strip or wire with 0.70% to 1.20% C in the quenched and tempered condition [31].

8.3.2 Steels for Quenched and Tempered springs:

Hot-formed quenched and tempered vehicle springs for low stresses are made from unalloyed steels containing 0.40% to 0.70% C.

Silicon alloyed steels with about 1% to 2% Si are employed for the production of quenched and tempered springs for bending stresses, especially for vehicle springs in railroad and automobile construction.

Frequently a small chromium addition of 0.20% to 0.40% is used for increasing the hardenability. Silicon raises the ratio of yield stress to tensile strength in the quenched and tempered condition as well as the retention of hardness in tempering, but also enhances the tendency towards decarburization. Therefore the use of steels is not appropriate for highly stressed springs [44].

Manganese alloyed spring steels are still employed to a small extent for vehicle springs (mainly for leaf, cup or annular buffer springs). Where is the manganese certainly increases hardenability and through hardening even in bigger cross-sections.

Chromium- and chromium-vanadium-steels are often preferred for helical and torsion bar springs in vehicle construction as well as for leaf and spiral spring that work under high stresses. These steels are used with advantage because of their high and uniform hardenability; they present no problems in heat treating and show a favourable behaviour under bending and tensional stress. Spring steels containing about 0.6% C, 0.5% Cr, 0.6% Ni and 0.2% Mo are used for heavy leaf and helical springs, in sizes up to 45 mm diameter [31].

8.3.3 Springs steels for high temperature service

If strength requirements at temperatures up to about 300 ^{0}C are to be met, chromium-vanadium, silicon-chromium, and silicon-chromium-molybdenum steels may be considered. At higher temperatures chromium-molybdenum-vanadium steels and sometimes even tungsten alloyed hot working steels are used. Theses steels are necessary for springs to work at high temperature stresses in valves, seals, exhaust valves in engines, steam turbine [45].

Steel selection depends, additionally on the properties at room temperature, on the yield stress at up to about 350 ^{0}C and at still higher temperatures on the creep limits. Accordingly the working stresses must be reduced and the effects of higher temperatures must be considered in view of the fact that creep and relaxation increase whereas the modulus of elasticity (Young's modulus) and shear modulus, tensile strength and yield stress decreases considerably [31].

8.3.4 Spring steels for low temperature services

In the selection of cryogenic steels for springs with good toughness at low temperatures attention must be paid to the fact that decreasing temperatures are accompanied by increasing tensile strength and notch sensitivity due to loss of toughness [45]. Depending on service conditions and, above all, on service temperature, chromium-molybdenum and chromium-nickel-molybdenum quenched and tempered steels are used [31].

8.4 Mechanical properties required for spring steels

Springs are used in many different applications in mechanical engineering. Barring those that experience repeated cyclic stressing at high frequencies. The most important mechanical properties required to for springs design are [13]:

1. Yield strength (0.2% proof stress): yield strength should be high enough such that it can withstand the stress that would be getting applied.
2. Resilience (σ_y^2/E): Because of the energy absorbed in the elastic stressing should be high, so resilience (σ_Y^2/E, where σ_Y is the yield strength, and E is modulus of elasticity) is required to be high.
3. Ductility: A sufficient degree of plastic deformation is maintained as a safeguard against fracture by overloading of the spring.
4. High fatigue strength under alternating and fluctuating stresses with a reserve for occasional or more frequent overloads.

Table (8.2) Mechanical properties for spring steels as in hardened and tempered condition.

Table 8-2 Mechanical properties for spring steels as hardened and tampered condition [4], [13], [24], [25], [26], [27], [30], [31]

Steel Grade Standards			Heat Treatment		Mechanical Properties for Spring Steels						Cost[2] $/kg $*10^{-1}$
BS	AISI	DIN	Quenching ^{0}C (medium)	Tempering ^{0}C	σ_Y Mpa	σ_{UTS} Mpa	Elong. %	E Gpa	Resilience[1]	Fatigue strength at 10^7 cycle Mpa	
060A62	1060	C60	830 (Oil)	205 ^{0}C	780	1103	13	212	2.9	458	0.827
				425 ^{0}C	765	1078	14	212	2.8	478	
				650 ^{0}C	670	965	17	212	2.1	417	
080A83	1080	--	810 (Oil)	205 ^{0}C	980	1310	12	208	4.6	516	0.860
				425 ^{0}C	950	1290	13	208	4.3	517	
				650 ^{0}C	600	890	21	208	1.7	395	
060A96	1095	CK101	800 (Oil)	205 ^{0}C	828	1290	10	208	3.3	517	0.885
				425 ^{0}C	773	1213	12	208	2.9	489	
				650 ^{0}C	553	898	21	208	1.5	397	
216M44	1144	--	845 (Oil)	205 ^{0}C	628	875	17	208	1.9	390	0.745
				425 ^{0}C	613	848	18	208	1.8	381	
				650 ^{0}C	503	723	23	208	1.2	341	
150M36	1340	36Mn5	830 (Oil)	205 ^{0}C	1593	1808	11	208	12.2	647	0.800
				425 ^{0}C	1153	1263	14	208	6.4	504	
				650 ^{0}C	623	800	22	208	1.9	366	
708M40	4150	50CrMo4	830 (Oil)	205 ^{0}C	1725	1930	10	207	14.4	678	0.952
				425 ^{0}C	1380	1518	13	207	9.2	573	
				650 ^{0}C	840	958	19	207	3.4	415	
--	5150	46Cr2	830 (Oil)	205 ^{0}C	1730	1945	5	207	14.5	682	0.970
				425 ^{0}C	1360	1448	9	207	8.9	554	
				650 ^{0}C	808	813	25	207	3.2	368	
527H60	5160	--	830 (Oil)	205 ^{0}C	1793	2220	4	209	15.4	748	0.985
				425 ^{0}C	1463	1605	10	209	10.2	595	
				650 ^{0}C	806	896	20	209	3.1	397	
735A51	6150	50CrV4	845 (Oil)	205 ^{0}C	1690	1930	8	207	13.8	678	0.990
				425 ^{0}C	1330	1438	10	207	8.5	551	
				650 ^{0}C	840	945	17	207	3.4	411	
708M40	8650	--	800 (Oil)	205 ^{0}C	1670	1938	10	211	13.2	675	1.010
				425 ^{0}C	1323	1448	12	211	8.3	554	
				650 ^{0}C	828	965	20	211	3.2	417	
805A60	8660	--	800 (Oil)	425 ^{0}C	1550	1633	13	211	11.4	603	1.150
				650 ^{0}C	958	1068	20	211	4.3	448	
251A58	9255	--	850 (Oil)	205 ^{0}C	2048	2103	1	211	19.9	720	0.834
				425 ^{0}C	1490	1610	8	211	10.5	597	
				650 ^{0}C	813	993	20	211	3.1	426	
251A60	9260	--	860 (Oil)	425 ^{0}C	1503	1760	8	207	10.9	635	0.846
				650 ^{0}C	813	980	20	207	3.2	422	
--	50B60	--	820 (Oil)	425 ^{0}C	1383	1510	11	207	9.2	571	0.848
		--		650 ^{0}C	780	898	19	207	2.9	396	
--	51B60	--	800 (Oil)	425 ^{0}C	1490	1633	11	207	10.7	603	0.850
				650 ^{0}C	870	965	20	207	3.7	417	
--	86B45	--	840 (Oil)	205 ^{0}C	1725	2033	10	207	14.4	703	0.850
				425 ^{0}C	1310	1408	11	207	8.3	543	
				650 ^{0}C	793	898	20	207	3.0	396	

[1]Resilience = σY2 / E where E is Young's Modulus.
[2]Cost is included row steel price and heat treatment cost (5% from row steel price), GRANTA material inspiration, CES EduPack 2006 & ETC company prices.

8.5 Selection of spring steels by using weighted property method

All design requirements for springs, yield strength, resilience ductility, fatigue strength, and cost are scaled by using Eq. (4.1 & 4.2) as discussed in chapter 4. These scaled properties are listed in table (8.3).

Table 8-3 Scaled property for spring steels

Steel Grade Standards			Condition	Scaled Values for Springs Steels				
BS	AISI	DIN		σ_Y	Elong %	Resilience	Fatigue Strength	Cost
060A62	1060	C60	H & T205 ^{0}C	38	52	14	64	90
060A62	1060	C60	H & T425 ^{0}C	37	56	14	66	90
060A62	1060	C60	H & T650 ^{0}C	33	68	11	58	90
080A83	1080	--	H & T205 ^{0}C	48	48	23	72	87
080A83	1080	--	H & T425 ^{0}C	46	52	22	72	87
080A83	1080	--	H & T650 ^{0}C	29	84	9	55	87
060A96	1095	CK101	H & T205 ^{0}C	40	40	17	72	84
060A97	1095	CK102	H & T425 ^{0}C	38	48	14	68	84
060A98	1095	CK103	H & T650 ^{0}C	27	84	7	55	84
216M44	1144	--	H & T205 ^{0}C	31	68	10	54	100
216M45	1144	--	H & T425 ^{0}C	30	72	9	53	100
216M46	1144	--	H & T650 ^{0}C	25	92	6	47	100
150M36	1340	36Mn5	H & T205 ^{0}C	78	44	61	90	93
150M37	1340	36Mn6	H & T425 ^{0}C	56	56	32	70	93
150M38	1340	36Mn7	H & T650 ^{0}C	30	88	9	51	93
708M40	4150	50CrMo4	H & T205 ^{0}C	84	40	72	94	78
708M40	4150	50CrMo4	H & T425 ^{0}C	67	52	46	80	78
708M40	4150	50CrMo4	H & T650 ^{0}C	41	76	17	58	78
--	5150	46Cr2	H & T205 ^{0}C	84	20	73	95	77
--	5150	46Cr2	H & T425 ^{0}C	66	36	45	77	77
--	5150	46Cr2	H & T650 ^{0}C	39	100	16	51	77
527H60	5160	--	H & T205 ^{0}C	88	16	77	104	76
527H60	5160	--	H & T425 ^{0}C	71	40	52	83	76
527H60	5160	--	H & T650 ^{0}C	39	80	16	55	76
735A51	6150	50CrV4	H & T205 ^{0}C	83	32	69	94	65
735A51	6150	50CrV4	H & T425 ^{0}C	65	40	43	77	65
735A51	6150	50CrV4	H & T650 ^{0}C	41	68	17	57	65
708M40	8650	--	H & T205 ^{0}C	82	40	66	94	61
708M40	8650	--	H & T425 ^{0}C	65	48	42	77	61
708M40	8650	--	H & T650 ^{0}C	40	80	16	58	61
805A60	8660	--	H & T425 ^{0}C	76	52	57	84	60
805A60	8660	--	H & T650 ^{0}C	47	80	22	62	60
251A58	9255	--	H & T205 ^{0}C	100	4	100	100	89
251A58	9255	--	H & T425 ^{0}C	73	32	53	83	89
251A58	9255	--	H & T650 ^{0}C	40	80	16	59	89
251A60	9260	--	H & T425 ^{0}C	73	32	55	88	88
251A60	9260	--	H & T650 ^{0}C	40	80	16	59	88
--	50B60	--	H & T425 ^{0}C	68	44	46	79	68
--	50B60	--	H & T650 ^{0}C	38	76	15	55	68
--	51B60	--	H & T425 ^{0}C	73	44	54	84	66
--	51B60	--	H & T650 ^{0}C	42	80	18	58	66
--	81B45	--	H & T205 ^{0}C	84	40	72	98	88
--	81B45	--	H & T425 ^{0}C	64	44	42	75	88
--	81B45	--	H & T650 ^{0}C	39	80	15	55	88

Maximum scaled property value

8.5.1 Selection of High strength-high Resilience spring steels

8.5.1.1 Relative importance of shaft requirements (Weighting factor)

The digital logic method is used to determine the weighting factors (α). Yield strength, resilience, ductility, fatigue strength, and cost will be given a degree of importance according to spring requirements as shown in Table (8.4).

Table 8-4 Weighting factors for high strength-high resilience springs steels.

Determination of relative importance of required properties for High strength –high resilience spring steels by using the digital logic method												
Properties Required (n)	**Number of possible decisions [N= n(n-1)/2]**										**Positive decisions(m)**	**Weighting factor (α)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Yield strength	**1**	**1**	**1**	**1**							**4**	**0.4**
Resilience	**0**				**1**	**1**	**1**				**3**	**0.3**
% Elong		**0**			**0**			**0**	**1**		**1**	**0.1**
Fatigue strength			**0**			**0**		**1**		**0**	**1**	**0.1**
Cost				**0**			**0**		**0**	**1**	**1**	**0.1**
											10	**1**

8.5.1.2 Relative importance of spring requirements (Weighting factor)

By using Eq. (4.3) the performance index for each property will be calculated and ranking will be made according to performance index for individual steel (highest 5 ranked steels are red colured), as shown in Table (8.5).

The results shows that (***BS 251A58, AISI 9255)*** steel in a hardened and tempered at 205 ^{0}C is the optimum choice for high strength-high resilience spring steels

Table 8-5 performance index & ranking of high strength-high resilience spring steels

Steel Grade Standards			Condition	Performance Index of Spring steels					Performance index (γ)	Ranking
BS	AISI	DIN		σ_Y	Elong. %	Resilience	Fatigue Strength	Cost		
060A62	1060	C60	H & T205 ^{0}C	15.2	5.2	4.3	6.4	9.0	40.1	
060A62	1060	C60	H & T425 ^{0}C	14.9	5.6	4.2	6.6	9.0	40.4	
060A62	1060	C60	H & T650 ^{0}C	13.1	6.8	3.2	5.8	9.0	37.9	
080A83	1080	--	H & T205 ^{0}C	19.1	4.8	7.0	7.2	8.7	46.7	
080A83	1080	--	H & T425 ^{0}C	18.6	5.2	6.5	7.2	8.7	46.1	
080A83	1080	--	H & T650 ^{0}C	11.7	8.4	2.6	5.5	8.7	36.9	
060A96	1095	CK101	H & T205 ^{0}C	16.2	4.0	5.0	7.2	8.4	40.7	
060A97	1095	CK102	H & T425 ^{0}C	15.1	4.8	4.3	6.8	8.4	39.4	
060A98	1095	CK103	H & T650 ^{0}C	10.8	8.4	2.2	5.5	8.4	35.4	
216M44	1144	--	H & T205 ^{0}C	12.3	6.8	2.9	5.4	10.0	37.3	
216M45	1144	--	H & T425 ^{0}C	12.0	7.2	2.7	5.3	10.0	37.2	
216M46	1144	--	H & T650 ^{0}C	9.8	9.2	1.8	4.7	10.0	35.6	
150M36	1340	36Mn5	H & T205 ^{0}C	31.1	4.4	18.4	9.0	9.3	72.2	5
150M37	1340	36Mn6	H & T425 ^{0}C	22.5	5.6	9.6	7.0	9.3	54.1	
150M38	1340	36Mn7	H & T650 ^{0}C	12.2	8.8	2.8	5.1	9.3	38.2	
708M40	4150	50CrMo4	H & T205 ^{0}C	33.7	4.0	21.7	9.4	7.8	76.6	4
708M40	4150	50CrMo4	H & T425 ^{0}C	27.0	5.2	13.9	8.0	7.8	61.8	
708M40	4150	50CrMo4	H & T650 ^{0}C	16.4	7.6	5.1	5.8	7.8	42.7	
--	5150	46Cr2	H & T205 ^{0}C	33.8	2.0	21.8	9.5	7.7	74.8	
--	5150	46Cr2	H & T425 ^{0}C	26.6	3.6	13.5	7.7	7.7	59.0	
--	5150	46Cr2	H & T650 ^{0}C	15.8	10.0	4.8	5.1	7.7	43.3	
527H60	5160	--	H & T205 ^{0}C	35.0	1.6	23.2	10.4	7.6	77.8	3
527H60	5160	--	H & T425 ^{0}C	28.6	4.0	15.5	8.3	7.6	63.9	
527H60	5160	--	H & T650 ^{0}C	15.7	8.0	4.7	5.5	7.6	41.5	
735A51	6150	50CrV4	H & T205 ^{0}C	33.0	3.2	20.8	9.4	6.5	72.9	
735A51	6150	50CrV4	H & T425 ^{0}C	26.0	4.0	12.9	7.7	6.5	57.0	
735A51	6150	50CrV4	H & T650 ^{0}C	16.4	6.8	5.1	5.7	6.5	40.5	
708M40	8650	--	H & T205 ^{0}C	32.6	4.0	19.9	9.4	6.1	72.0	
708M40	8650	--	H & T425 ^{0}C	25.8	4.8	12.5	7.7	6.1	56.9	
708M40	8650	--	H & T650 ^{0}C	16.2	8.0	4.9	5.8	6.1	40.9	
805A60	8660	--	H & T425 ^{0}C	30.3	5.2	17.2	8.4	6.0	67.0	
805A60	8660	--	H & T650 ^{0}C	18.7	8.0	6.6	6.2	6.0	45.5	
251A58	**9255**	**--**	**H & T205 ^{0}C**	**40.0**	**0.4**	**30.0**	**10.0**	**8.9**	**89.3**	**1**
251A58	9255	--	H & T425 ^{0}C	29.1	3.2	15.9	8.3	8.9	65.4	
251A58	9255	--	H & T650 ^{0}C	15.9	8.0	4.7	5.9	8.9	43.5	
251A60	9260	--	H & T425 ^{0}C	29.4	3.2	16.5	8.8	8.8	66.7	
251A60	9260	--	H & T650 ^{0}C	15.9	8.0	4.8	5.9	8.8	43.4	
--	50B60	--	H & T425 ^{0}C	27.0	4.4	13.9	7.9	6.8	60.1	
--	50B60	--	H & T650 ^{0}C	15.2	7.6	4.4	5.5	6.8	39.5	
--	51B60	--	H & T425 ^{0}C	29.1	4.4	16.2	8.4	6.6	64.7	
--	51B60	--	H & T650 ^{0}C	17.0	8.0	5.5	5.8	6.6	42.9	
--	86B45	--	H & T205 ^{0}C	33.7	4.0	21.7	9.8	8.8	77.9	2
--	86B45	--	H & T425 ^{0}C	25.6	4.4	12.5	7.5	8.8	58.8	
--	86B45	--	H & T650 ^{0}C	15.5	8.0	4.6	5.5	8.8	42.3	

8.5.2 Selection of Ductile springs steels

8.5.2.1 Relative importance of shaft requirements (Weighting factor)

By using the digital logic method the weighing factor (α) for springs requirements are calculated, where the parentage of elongation (ductility) considered as highest importance requirement, as shown in Table (8.6).

Table 8-6 Weighting factors for ductile springs steels.

Determination of relative importance of required properties for ductile Spring steels by using the digital logic method												
Properties Required (n)	**Number of possible decisions [N= n(n-1)/2]**										**Positive decisions (m)**	**Weighting factor (α)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Yield strength	**1**	**0**	**0**	**1**							**2**	**0.2**
Resilience	**0**				**0**	**1**	**1**				**2**	**0.2**
Ductility (% Elong)		**1**			**1**			**1**	**1**		**4**	**0.4**
Fatigue strength			**1**			**0**		**0**		**0**	**1**	**0.1**
Cost				**0**			**0**		**0**	**1**	**1**	**0.1**
											10	**1**

8.5.2.2 Relative importance of spring requirements (Weighting factor)

Performance index calculations are shown that the optimum steel can be used for springs, when the ductility is the first requirement for spring selection is ***(AISI 86B45)*** steel in hardened and tempered at 205 ^{0}C. The ranking list (Highest 5 ranked steels are red coloured) for this application is shown in Table (8.7).

Table 8-7 performance index & ranking of ductile spring steels

Steel Grade Standards			Condition	Performance Index of Spring steels					Performance index (γ)	Ranking
BS	AISI	DIN		σ_Y	Elong %	Resilience	Fatigue Strength	Cost		
060A62	1060	C60	H & T205 ^{0}C	7.6	20.8	2.9	6.4	9.0	46.7	
060A62	1060	C60	H & T425 ^{0}C	7.5	22.4	2.8	6.6	9.0	48.3	
060A62	1060	C60	H & T650 ^{0}C	6.5	27.2	2.1	5.8	9.0	50.7	
080A83	1080	--	H & T205 ^{0}C	9.6	19.2	4.6	7.2	8.7	49.2	
080A83	1080	--	H & T425 ^{0}C	9.3	20.8	4.4	7.2	8.7	50.3	
080A83	1080	--	H & T650 ^{0}C	5.9	33.6	1.7	5.5	8.7	55.3	
060A96	1095	CK101	H & T205 ^{0}C	8.1	16.0	3.3	7.2	8.4	43.0	
060A97	1095	CK102	H & T425 ^{0}C	7.5	19.2	2.9	6.8	8.4	44.9	
060A98	1095	CK103	H & T650 ^{0}C	5.4	33.6	1.5	5.5	0.0	46.0	
216M44	1144	--	H & T205 ^{0}C	6.1	27.2	1.9	5.4	10.0	50.7	
216M45	1144	--	H & T425 ^{0}C	6.0	28.8	1.8	5.3	10.0	51.9	
216M46	1144	--	H & T650 ^{0}C	4.9	36.8	1.2	4.7	10.0	57.7	
150M36	1340	36Mn5	H & T205 ^{0}C	15.6	17.6	12.3	9.0	9.3	63.7	4
150M37	1340	36Mn6	H & T425 ^{0}C	11.3	22.4	6.4	7.0	9.3	56.4	
150M38	1340	36Mn7	H & T650 ^{0}C	6.1	35.2	1.9	5.1	9.3	57.6	
708M40	4150	50CrMo4	H & T205 ^{0}C	16.8	16.0	14.5	9.4	7.8	64.6	2
708M40	4150	50CrMo4	H & T425 ^{0}C	13.5	20.8	9.3	8.0	7.8	59.3	
708M40	4150	50CrMo4	H & T650 ^{0}C	8.2	30.4	3.4	5.8	7.8	55.6	
--	5150	46Cr2	H & T205 ^{0}C	16.9	8.0	14.5	9.5	7.7	56.6	
--	5150	46Cr2	H & T425 ^{0}C	13.3	14.4	9.0	7.7	7.7	52.0	
--	5150	46Cr2	H & T650 ^{0}C	7.9	40.0	3.2	5.1	7.7	63.9	3
527H60	5160	--	H & T205 ^{0}C	17.5	6.4	15.5	10.4	7.6	57.3	
527H60	5160	--	H & T425 ^{0}C	14.3	16.0	10.3	8.3	7.6	56.4	
527H60	5160	--	H & T650 ^{0}C	7.9	32.0	3.1	5.5	7.6	56.1	
735A51	6150	50CrV4	H & T205 ^{0}C	16.5	12.8	13.9	9.4	7.5	60.1	
735A51	6150	50CrV4	H & T425 ^{0}C	13.0	16.0	8.6	7.7	7.5	52.8	
735A51	6150	50CrV4	H & T650 ^{0}C	8.2	27.2	3.4	5.7	7.5	52.1	
708M40	8650	--	H & T205 ^{0}C	16.3	16.0	13.3	9.4	7.4	62.4	
708M40	8650	--	H & T425 ^{0}C	12.9	19.2	8.3	7.7	7.4	55.5	
708M40	8650	--	H & T650 ^{0}C	8.1	32.0	3.3	5.8	7.4	56.5	
805A60	8660	--	H & T425 ^{0}C	15.1	20.8	11.5	8.4	6.5	62.2	5
805A60	8660	--	H & T650 ^{0}C	9.4	32.0	4.4	6.2	6.5	58.4	
251A58	9255	--	H & T205 ^{0}C	20.0	1.6	20.0	10.0	8.9	60.5	
251A58	9255	--	H & T425 ^{0}C	14.6	12.8	10.6	8.3	8.9	55.2	
251A58	9255	--	H & T650 ^{0}C	7.9	32.0	3.2	5.9	8.9	57.9	
251A60	9260	--	H & T425 ^{0}C	14.7	12.8	11.0	8.8	8.8	56.1	
251A60	9260	--	H & T650 ^{0}C	7.9	32.0	3.2	5.9	8.8	57.8	
--	50B60	--	H & T425 ^{0}C	13.5	17.6	9.3	7.9	8.8	57.1	
--	50B60	--	H & T650 ^{0}C	7.6	30.4	3.0	5.5	8.8	55.3	
--	51B60	--	H & T425 ^{0}C	14.6	17.6	10.8	8.4	8.8	60.1	
--	51B60	--	H & T650 ^{0}C	8.5	32.0	3.7	5.8	8.8	58.7	
--	86B45	--	H & T205 ^{0}C	16.8	16.0	14.5	9.8	8.8	65.8	1
--	86B45	--	H & T425 ^{0}C	12.8	17.6	8.3	7.5	8.8	55.0	
--	86B45	--	H & T650 ^{0}C	7.7	32.0	3.1	5.5	8.8	57.1	

8.5.3 Selection of high fatigue strength spring steels

8.5.3.1 Relative importance of spring requirements (Weighting factor)

By using a digital logic method a weighing factor (α) for each property will be determined as shown in Table (8.8).

Table 8-8 Weighting factors for high fatigue strength springs steels

Determination of relative importance factor for high fatigue strength spring steels by using the digital logic method												
Properties Required (n)	**Number of possible decisions [N= n(n-1)/2]**										**Positive decisions (m)**	**Weighting factor (α)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Yield strength	**1**	**1**	**0**	**0**							**2**	**0.2**
Resilience	**0**				**1**	**0**	**1**				**2**	**0.2**
% Elong		**0**			**0**			**0**	**1**		**1**	**0.1**
Fatigue strength			**1**			**1**		**1**		**1**	**4**	**0.4**
Cost				**1**			**0**		**0**	**0**	**1**	**0.1**
											10	**1**

8.5.3.2 Performance index (γ) for high fatigue strength springs steels

From the table (8.9) it's clear that ***(BS 251A58, AISI 9255***) steel is the best steel can be used for fatigue springs application in hardened and tempered at 205 ^{0}C condition.

The ranking list (highest 5 ranked steels are red colured) is made as in table (8.9).

Table 8-9 performance index & ranking of high fatigue strength spring steels

Steel Grade Standards			Condition	Performance Index of Spring steels					Performance index (γ)	Ranking
BS	AISI	DIN		σ_Y	Elong.%	Resilience	Fatigue Strength	Cost		
060A62	1060	C60	H & T205 ^{0}C	7.6	5.2	2.9	25.4	9.0	50.2	
060A62	1060	C60	H & T425 ^{0}C	7.5	5.6	2.8	26.6	9.0	51.4	
060A62	1060	C60	H & T650 ^{0}C	6.5	6.8	2.1	23.2	9.0	47.6	
080A83	1080	--	H & T205 ^{0}C	9.6	4.8	4.6	28.7	8.7	56.3	
080A83	1080	--	H & T425 ^{0}C	9.3	5.2	4.4	28.7	8.7	56.2	
080A83	1080	--	H & T650 ^{0}C	5.9	8.4	1.7	21.9	8.7	46.6	
060A96	1095	CK101	H & T205 ^{0}C	8.1	4.0	3.3	28.7	8.4	52.5	
060A97	1095	CK102	H & T425 ^{0}C	7.5	4.8	2.9	27.2	8.4	50.8	
060A98	1095	CK103	H & T650 ^{0}C	5.4	8.4	1.5	22.1	8.4	45.8	
216M44	1144	--	H & T205 ^{0}C	6.1	6.8	1.9	21.7	10.0	46.5	
216M45	1144	--	H & T425 ^{0}C	6.0	7.2	1.8	21.2	10.0	46.2	
216M46	1144	--	H & T650 ^{0}C	4.9	9.2	1.2	18.9	10.0	44.3	
150M36	1340	36Mn5	H & T205 ^{0}C	15.6	4.4	12.3	35.9	9.3	77.5	
150M37	1340	36Mn6	H & T425 ^{0}C	11.3	5.6	6.4	28.0	9.3	60.6	
150M38	1340	36Mn7	H & T650 ^{0}C	6.1	8.8	1.9	20.3	9.3	46.4	
708M40	4150	50CrMo4	H & T205 ^{0}C	16.8	4.0	14.5	37.7	7.8	80.8	4
708M40	4150	50CrMo4	H & T425 ^{0}C	13.5	5.2	9.3	31.8	7.8	67.6	
708M40	4150	50CrMo4	H & T650 ^{0}C	8.2	7.6	3.4	23.1	7.8	50.1	
--	5150	46Cr2	H & T205 ^{0}C	16.9	2.0	14.5	37.9	7.7	79.0	5
--	5150	46Cr2	H & T425 ^{0}C	13.3	3.6	9.0	30.8	7.7	64.3	
--	5150	46Cr2	H & T650 ^{0}C	7.9	10.0	3.2	20.4	7.7	49.2	
527H60	5160	--	H & T205 ^{0}C	17.5	1.6	15.5	41.6	7.6	83.7	2
527H60	5160	--	H & T425 ^{0}C	14.3	4.0	10.3	33.1	7.6	69.2	
527H60	5160	--	H & T650 ^{0}C	7.9	8.0	3.1	22.1	7.6	48.6	
735A51	6150	50CrV4	H & T205 ^{0}C	16.5	3.2	13.9	37.7	6.5	77.7	
735A51	6150	50CrV4	H & T425 ^{0}C	13.0	4.0	8.6	30.6	6.5	62.7	
735A51	6150	50CrV4	H & T650 ^{0}C	8.2	6.8	3.4	22.8	6.5	47.7	
708M40	8650	--	H & T205 ^{0}C	16.3	4.0	13.3	37.5	6.1	77.2	
708M40	8650	--	H & T425 ^{0}C	12.9	4.8	8.3	30.8	6.1	62.9	
708M40	8650	--	H & T650 ^{0}C	8.1	8.0	3.3	23.2	6.1	48.6	
805A60	8660	--	H & T425 ^{0}C	15.1	5.2	11.5	33.5	6.0	71.3	
805A60	8660	--	H & T650 ^{0}C	9.4	8.0	4.4	24.9	6.0	52.6	
251A58	**9255**	**--**	**H & T205 ^{0}C**	**20.0**	**0.4**	**20.0**	**40.0**	**8.9**	**89.3**	**1**
251A58	9255	--	H & T425 ^{0}C	14.6	3.2	10.6	33.2	8.9	70.4	
251A58	9255	--	H & T650 ^{0}C	7.9	8.0	3.2	23.7	8.9	51.7	
251A60	9260	--	H & T425 ^{0}C	14.7	3.2	11.0	35.3	8.8	72.9	
251A60	9260	--	H & T650 ^{0}C	7.9	8.0	3.2	23.4	8.8	51.4	
--	50B60	--	H & T425 ^{0}C	13.5	4.4	9.3	31.7	6.8	65.7	
--	50B60	--	H & T650 ^{0}C	7.6	7.6	3.0	22.0	6.8	46.9	
--	51B60	--	H & T425 ^{0}C	14.6	4.4	10.8	33.5	6.6	69.8	
--	51B60	--	H & T650 ^{0}C	8.5	8.0	3.7	23.2	6.6	49.9	
--	86B45	--	H & T205 ^{0}C	16.8	4.0	14.5	39.1	8.8	83.1	3
--	86B45	--	H & T425 ^{0}C	12.8	4.4	8.3	30.2	8.8	64.5	
--	86B45	--	H & T650 ^{0}C	7.7	8.0	3.1	22.0	8.8	49.6	

8.5.4 Selection of Low cost spring steels

8.5.4.1 Relative importance of spring requirements (Weighting factor)

Cost can be considered as most importance requirement when design select the optimum steel for springs application.

The cost will be given highest weighting factor by using a digital logic method, as shown in Table (8.10).

Table 8-10 Weighting factors for low cost springs steels.

Determination of relative importance factor for low cost spring steels by using the digital logic method												
Properties Required (n)	Number of possible decisions [N= n(n-1)/2]										Positive decisions (m)	Weighting factor (α)
	1	2	3	4	5	6	7	8	9	10		
Yield strength	1	1	0	0							2	0.2
Resilience	0				1	1	0				2	0.2
% Elong		0			0			1	0		1	0.1
Fatigue strength			1			0		0		0	1	0.1
Cost				1			1		1	1	4	0.4
											10	1

8.5.4.2 Performance index (γ) for low cost springs steels

The performance index for candidate steels indicates that (***251A58, AISI 9***) steel in hardened and tempered at 205 ^{0}C condition is the best choice can be used for low cost springs, this is shown in table (8.11) shows the ranking list (Highest 5 ranked steels are red colured) for this application.

Table 8-11 performance index & ranking of high fatigue strength spring steels

Steel Grade Standards			Condition	Performance Index of Spring steels					Performance index (γ)	Ranking
BS	AISI	DIN		σ_Y	Elong %	Resilience	Fatigue Strength	Cost		
060A62	1060	C60	H & T205 ^{0}C	7.6	5.2	2.9	6.4	36.0	58.1	
060A62	1060	C60	H & T425 ^{0}C	7.5	5.6	2.8	6.6	36.0	58.5	
060A62	1060	C60	H & T650 ^{0}C	6.5	6.8	2.1	5.8	36.0	57.3	
080A83	1080	--	H & T205 ^{0}C	9.6	4.8	4.6	7.2	34.7	60.8	
080A83	1080	--	H & T425 ^{0}C	9.3	5.2	4.4	7.2	34.7	60.7	
080A83	1080	--	H & T650 ^{0}C	5.9	8.4	1.7	5.5	34.7	56.1	
060A96	1095	CK101	H & T205 ^{0}C	8.1	4.0	3.3	7.2	33.7	56.3	
060A97	1095	CK102	H & T425 ^{0}C	7.5	4.8	2.9	6.8	33.7	55.7	
060A98	1095	CK103	H & T650 ^{0}C	5.4	8.4	1.5	5.5	33.7	54.5	
216M44	1144	--	H & T205 ^{0}C	6.1	6.8	1.9	5.4	40.0	60.3	
216M45	1144	--	H & T425 ^{0}C	6.0	7.2	1.8	5.3	40.0	60.3	
216M46	1144	--	H & T650 ^{0}C	4.9	9.2	1.2	4.7	40.0	60.1	
150M36	1340	36Mn5	H & T205 ^{0}C	15.6	4.4	12.3	9.0	37.3	78.5	3
150M37	1340	36Mn6	H & T425 ^{0}C	11.3	5.6	6.4	7.0	37.3	67.5	
150M38	1340	36Mn7	H & T650 ^{0}C	6.1	8.8	1.9	5.1	37.3	59.1	
708M40	4150	50CrMo4	H & T205 ^{0}C	16.8	4.0	14.5	9.4	31.3	76.0	4
708M40	4150	50CrMo4	H & T425 ^{0}C	13.5	5.2	9.3	8.0	31.3	67.2	
708M40	4150	50CrMo4	H & T650 ^{0}C	8.2	7.6	3.4	5.8	31.3	56.3	
--	5150	46Cr2	H & T205 ^{0}C	16.9	2.0	14.5	9.5	30.7	73.6	
--	5150	46Cr2	H & T425 ^{0}C	13.3	3.6	9.0	7.7	30.7	64.3	
--	5150	46Cr2	H & T650 ^{0}C	7.9	10.0	3.2	5.1	30.7	56.9	
527H60	5160	--	H & T205 ^{0}C	17.5	1.6	15.5	10.4	30.3	75.2	5
527H60	5160	--	H & T425 ^{0}C	14.3	4.0	10.3	8.3	30.3	67.1	
527H60	5160	--	H & T650 ^{0}C	7.9	8.0	3.1	5.5	30.3	54.8	
735A51	6150	50CrV4	H & T205 ^{0}C	16.5	3.2	13.9	9.4	25.9	68.9	
735A51	6150	50CrV4	H & T425 ^{0}C	13.0	4.0	8.6	7.7	25.9	59.2	
735A51	6150	50CrV4	H & T650 ^{0}C	8.2	6.8	3.4	5.7	25.9	50.1	
708M40	8650	--	H & T205 ^{0}C	16.3	4.0	13.3	9.4	24.2	67.2	
708M40	8650	--	H & T425 ^{0}C	12.9	4.8	8.3	7.7	24.2	58.0	
708M40	8650	--	H & T650 ^{0}C	8.1	8.0	3.3	5.8	24.2	49.4	
805A60	8660	--	H & T425 ^{0}C	15.1	5.2	11.5	8.4	23.8	64.0	
805A60	8660	--	H & T650 ^{0}C	9.4	8.0	4.4	6.2	23.8	51.8	
251A58	**9255**	**--**	**H & T205 ^{0}C**	**20.0**	**0.4**	**20.0**	**10.0**	**35.7**	**86.1**	**1**
251A58	9255	--	H & T425 ^{0}C	14.6	3.2	10.6	8.3	35.7	72.4	
251A58	9255	--	H & T650 ^{0}C	7.9	8.0	3.2	5.9	35.7	60.7	
251A60	9260	--	H & T425 ^{0}C	14.7	3.2	11.0	8.8	35.2	72.9	
251A60	9260	--	H & T650 ^{0}C	7.9	8.0	3.2	5.9	35.2	60.2	
--	50B60	--	H & T425 ^{0}C	13.5	4.4	9.3	7.9	27.1	62.2	
--	50B60	--	H & T650 ^{0}C	7.6	7.6	3.0	5.5	27.1	50.8	
--	51B60	--	H & T425 ^{0}C	14.6	4.4	10.8	8.4	26.4	64.5	
--	51B60	--	H & T650 ^{0}C	8.5	8.0	3.7	5.8	26.4	52.3	
--	86B45	--	H & T205 ^{0}C	16.8	4.0	14.5	9.8	35.1	80.1	2
--	86B45	--	H & T425 ^{0}C	12.8	4.4	8.3	7.5	35.1	68.1	
--	86B45	--	H & T650 ^{0}C	7.7	8.0	3.1	5.5	35.1	59.4	

Chapter 9

9 MZ STEEL SELECTOR PROGRAM

9.1 Introduction

The materials selection starts by narrowing down the range of available alternatives to manageable number. This preliminary (course screening) selection of materials can be done at the early design stage, but, as the group of materials selected for specific design, the task will be more sophisticated, and needs for computer's help.

A visual basic computer program based on access Microsoft and weighted property method is developed to allow the designer to select the optimum steel for specific machine design application (gears, shafts, fasteners, and springs).

The selection criterion is depending on the design requirements, and the experience of the designer will play the main role for selection.

Each design requirements will have a degree of importance depending on priority of the required requirements. These requirements included mechanical properties and cost.

Any change on the priority of the design requirements will create spontaneously a new ranking steel list for specified machine application.

The following procedure will show the how the **MZ Steel Selector** works and how the steel ranking will be changed according to design requirements. Chemical compositions, mechanical properties, and heat treatments conditions are considered in the program, and the ranking steel list will be provided in the three steel designation standard, British (BS), American (AISI), and Germany (DIN).

9.2 Start the program and choose the machine application

By using visual basic software, the steel selector program will be called, and the start window will be displayed, as shown in figure as shown in figure (9.1).

Figure 9-1 Start of the MZ Steel Selector programs

9.3 Choose the machine application

Four machine applications are placed in the steel selector program, and the designer can choose which application will design, they are located on the left side of the window. For example gears application is chosen figure (9.2).

Figure 9-2 Chosen of gear application

9.4 Select priority (relative importance) of the design requirements

Each machine application has design requirements (mechanical properties & cost) that the designer should considered before select appropriate steel, and they will be seen on the left hand of the window, as shown in figure (9.2).

For example gears requirements are wear resistance, bending fatigue strength, impact strength, cost, and also machinability will be considered in the performance index calculations.

On the right hand of the previous window there are four empty spaces which will be filled according of the requirements priority. For example, if the fatigue strength is the most important requirement for gears; it will be put in the first (top) space by clicking on the fatigue strength icon, and the other requirements will put in the next spaces, and so on, as shown in figure (9.3).

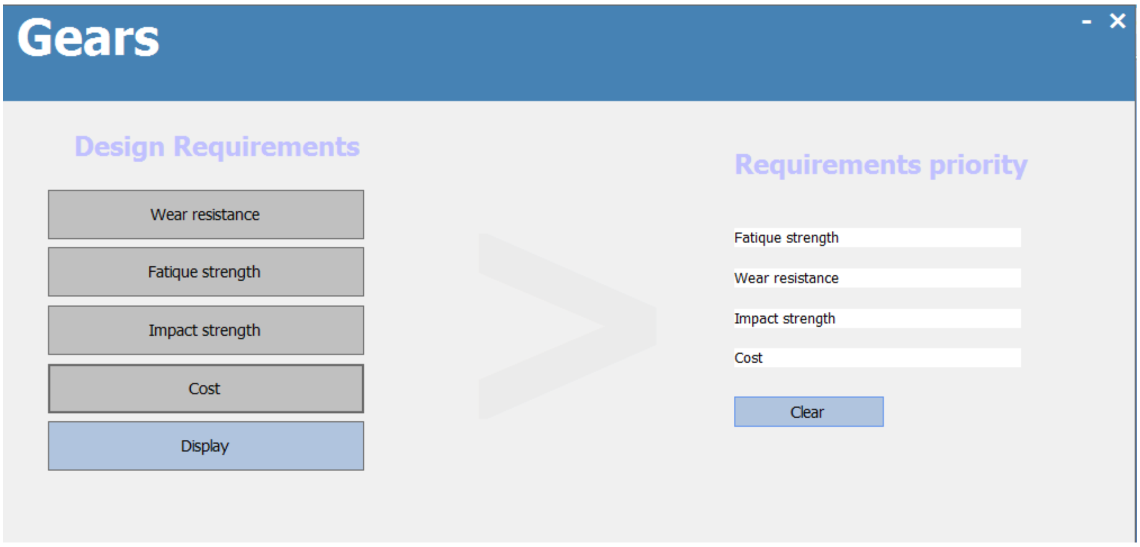
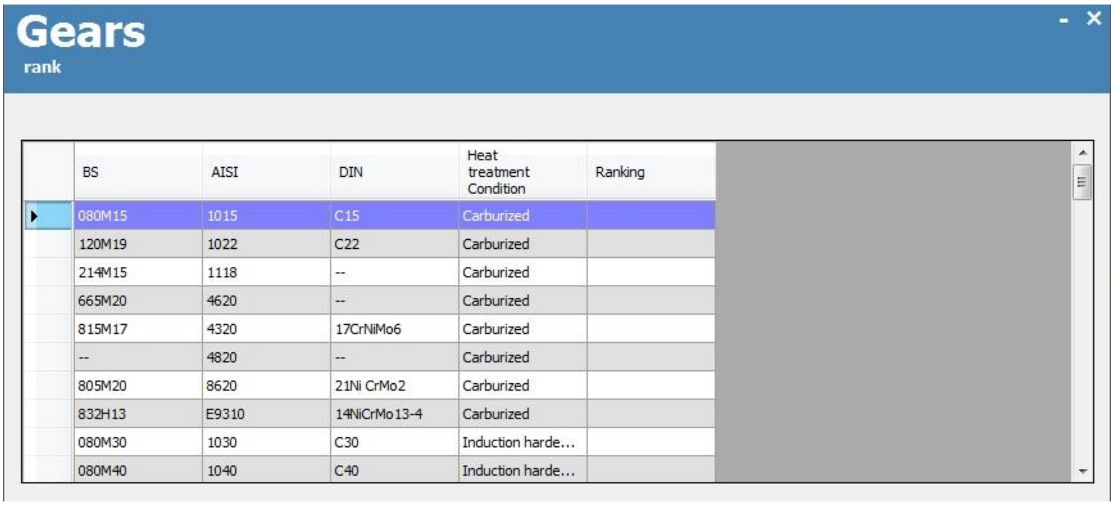


Figure 9-3 Select the requirements priority for specified application

9.5 List of ranking steels and select the optimum steel

After the requirements priority has been selected, the ranking list can be called by clicking on the display icon as shown in figure (9.4).

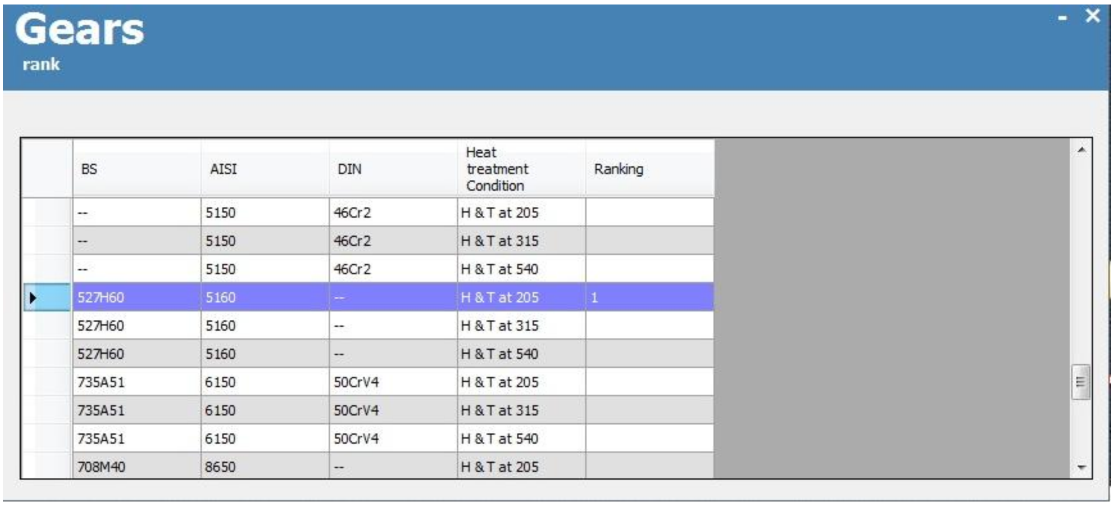


BS	AISI	DIN	Heat treatment Condition	Ranking
080M15	1015	C15	Carburized	
120M19	1022	C22	Carburized	
214M15	1118	--	Carburized	
665M20	4620	--	Carburized	
815M17	4320	17CrNiMo6	Carburized	
--	4820	--	Carburized	
805M20	8620	21Ni CrMo2	Carburized	
832H13	E9310	14NiCrMo13-4	Carburized	
080M30	1030	C30	Induction harde...	
080M40	1040	C40	Induction harde...	

Figure 9-4 Ranking list for high fatigue strength gear steels

9.6 Optimum ranked steel

By scrolled dawn the bar on right hand of the window, the optimum steel for specified application will be shown as number (1) on the last right hand column, as shown in figure (9.4), and highest five ranked is also shown in the column.



BS	AISI	DIN	Heat treatment Condition	Ranking
--	5150	46Cr2	H & T at 205	
--	5150	46Cr2	H & T at 315	
--	5150	46Cr2	H & T at 540	
527H60	5160	--	H & T at 205	1
527H60	5160	--	H & T at 315	
527H60	5160	--	H & T at 540	
735A51	6150	50CrV4	H & T at 205	
735A51	6150	50CrV4	H & T at 315	
735A51	6150	50CrV4	H & T at 540	
708M40	8650	--	H & T at 205	

Figure 9-5 optimum steel for high fatigue strength gears

9.7 Chemical compositions & mechanical properties

For each steel , the designer can obtain information about the chemical compositions, mechanical properties in specified heat treatment condition by clicking on the selected steel bar , the designation (BS, AISI, & DIN) of the steel will be on the top of the window ,as shown in figure (9.6 & 9.7).

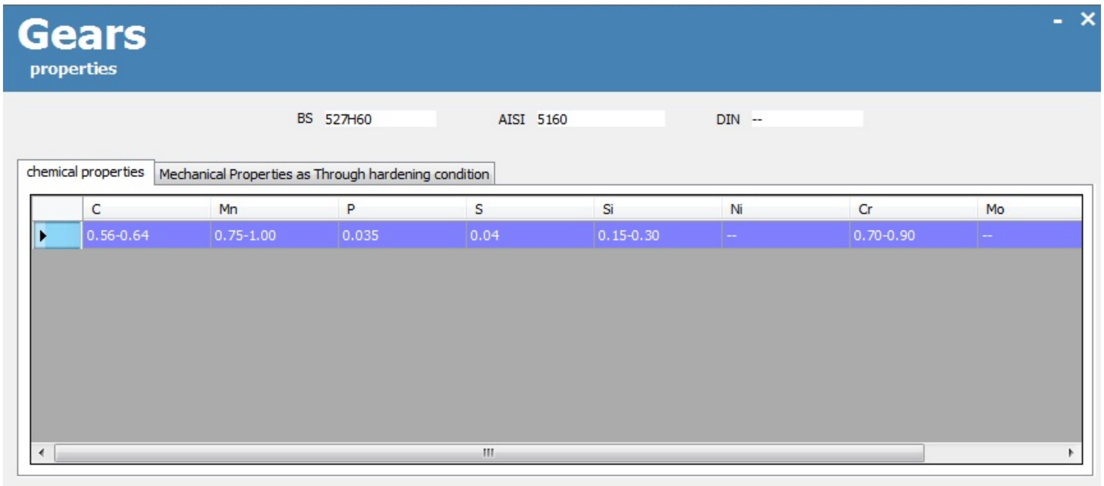


Figure 9-6 Chemical compositions of optimum gear steels for high fatigue strength application

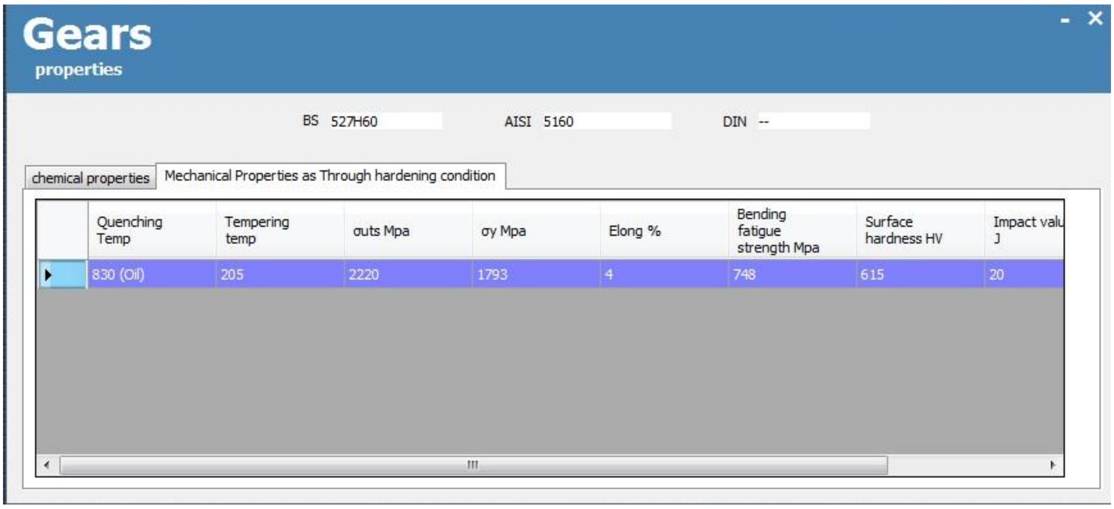


Figure 9-7 Mechanical properties and heat treatment condition of optimum gear steels for high fatigue strength application

Chapter 10

10 Conclusion

Material selection is a translation of design requirements to the materials specifications.

Stages of selection process can be summarized as follows:

1. Defining functions, and translating to required properties.
2. Selecting available material from a large database (go/no go).
3. Screening materials more closely.
4. Ranking by using quantitative method & finding best candidates.
5. Final material Choice.

It is concluded that the designer is responsible for the selection of steel to produce any machine component. This selection process requires the designer to find the real data and information on the mechanical properties required, and also knowing different heat treatment techniques that improve these properties.

However, in most application the selected steels must satisfy more than one performance requirement. A computer program based on the weighted properties method has been developed to assist in the selection of the optimum steel for machine components such as gears, shafts, fasteners, and springs. The required properties and attributes are ranked based on the strict adherent to the requirements taking into account how importance requirements are, and the cost considered as one of the properties.

From the performance index calculations, its clear that ***(BS 527H60, AISI 5160)*** steel in hardened and tempered at 205 ^{0}C conditions is the better steel for gears when the fatigue strength is the most important requirement, ***(BS 905M31)*** steel in nitrided condition when impact strength and wear resistance are most important, and ***(BS 530M40, AISI 1030, DIN C30)*** steel in induction hardened condition is the best when the cost considered as the most importance requirement.

For the shafts when the yield strength, fatigue strength , and cost are specified as an important property, ***(AISI 5150, DIN 46Cr2)*** steel in hardened and tempered at 205 ^{0}C condition will be the best choice, but for wear resistance ***(BS 823M30, AISI 8740, DIN 30CrNiMo8***) steel in hardened and tempered at 205 ^{0}C condition is the optimum.

In the Fasteners application the steel should possess high yield and fatigue strength, high hardness and toughness, so the (***BS 823M30, AISI 8740, DIN 30CrNiMo8***) steel is the best choice to be used for fasteners, which satisfies most of the required properties with low cost.

For high strength – high resilience springs , ***(BS 251A58, AISI 9255***) steel will be the finest selection in hardened and tempered at 205 ^{0}C condition, also can be used even when the cost is the most important requirement. However, ***(AISI 81B45)*** steel in hardened and tempered at 205 ^{0}C condition can be used when the ductile springs are required.

RECOMMENDATIONS FOR FURTHER WORK

More researches are required for:

- Selection of steel based on other properties such as chemical and physical properties.
- Selection of steel for other machine design application such as sheet steels applications, dies and moulds, cutting tools, & etc...
- Use other materials (stainless steels, Aluminium, copper, polymers, and etc.).
- Failures modes of the machine elements need to be studied and considering in the selection process.
- More focus on identification of the weighting factor for each design requirements.
- More concentration is required for manufacturing cost of machine components

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APPENDIX

Codes of the MZ steel selector software program

```
Module Module1s

    Public con1_Gears As OleDb.OleDbConnection
    Public con1_Shafts As OleDb.OleDbConnection
    Public con1_Fasteners As OleDb.OleDbConnection
    Public con1_Springs As OleDb.OleDbConnection

    Public cmd1 As OleDb.OleDbCommand
    Public DA1 As OleDb.OleDbDataAdapter
    Public DA2 As OleDb.OleDbDataAdapter

    Public table1 As New DataTable
    Public qt_carburized As New DataTable
    Public qt_inducted As New DataTable
    Public qt_TH As New DataTable
    Public qt_nitrided As New DataTable
    Public qt_chemical As New DataTable

    Public BS_val As String
    Public AISI_val As String
    Public DIN_val As String
    Public Heat_treat_val As String


End Module

============================================================
==================================

Public Class Form1

    Private Sub Form1_Load(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles MyBase.Load

        con1_Gears = New OleDb.OleDbConnection
        con1_Gears.ConnectionString = "provider
=microsoft.jet.oledb.4.0;data
source=C:\MZ_steel_selector\Data\Gears.mdb"
        con1_Gears.Open()

        con1_Shafts = New OleDb.OleDbConnection
```

```
        con1_Shafts.ConnectionString       =       "provider
=microsoft.jet.oledb.4.0;data
source=C:\MZ_steel_selector\Data\Shaft.mdb"
        con1_Shafts.Open()

        con1_Fasteners = New OleDb.OleDbConnection
        con1_Fasteners.ConnectionString     =     "provider
=microsoft.jet.oledb.4.0;data
source=C:\MZ_steel_selector\Data\Fasteners.mdb"
        con1_Fasteners.Open()

        con1_Springs = New OleDb.OleDbConnection
        con1_Springs.ConnectionString      =      "provider
=microsoft.jet.oledb.4.0;data
source=C:\MZ_steel_selector\Data\Springs.mdb"
        con1_Springs.Open()

        'cmd1 = New OleDb.OleDbCommand
        'DA1 = New OleDb.OleDbDataAdapter

    End Sub

    Private    Sub    Button1_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button1.Click
        Form2.Show()
        Me.Hide()

    End Sub

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click

        End

    End Sub

    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub

    Private    Sub    Button5_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button5.Click
```

```
MsgBox(System.AppDomain.CurrentDomain.BaseDirectory())
        MsgBox(Application.StartupPath())
    End Sub

    Private    Sub    Button2_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button2.Click

        shafts_main_frm.Show()
        Me.Hide()

    End Sub

    Private    Sub    Button3_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button3.Click
        fasteners_main_frm.Show()
        Me.Hide()

    End Sub

    Private    Sub    Button4_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button4.Click
        springs_main_frm.Show()
        Me.Hide()

    End Sub
End Class

==========================================================
===========================

Public Class Form2

    Private    Sub    Button1_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button1.Click

        If   TextBox1.Text   =   "Wear   resistance"   Or
TextBox2.Text = "Wear resistance" Or TextBox3.Text = "Wear
resistance" Or TextBox4.Text = "Wear resistance" Then Exit
Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Wear resistance"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Wear resistance"
```

```
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Wear resistance"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Wear resistance"
        End If
    End Sub

    Private Sub Button2_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button2.Click

        If TextBox1.Text = "Fatique strength" Or
TextBox2.Text = "Fatique strength" Or TextBox3.Text =
"Fatique strength" Or TextBox4.Text = "Fatique strength"
Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Fatique strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Fatique strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Fatique strength"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Fatique strength"
        End If

    End Sub

    Private Sub Button3_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button3.Click

        If TextBox1.Text = "Impact strength" Or
TextBox2.Text = "Impact strength" Or TextBox3.Text =
"Impact strength" Or TextBox4.Text = "Impact strength" Then
Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Impact strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Impact strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Impact strength"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Impact strength"
        End If

    End Sub
```

```
    Private    Sub    Button4_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button4.Click

        If TextBox1.Text = "Cost" Or TextBox2.Text = "Cost"
Or TextBox3.Text = "Cost" Or TextBox4.Text = "Cost" Then
Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Cost"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Cost"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Cost"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Cost"
        End If

    End Sub

    Private    Sub    Button5_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button5.Click

        Select Case TextBox1.Text

            Case "Wear resistance"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText   =   "select   *   from
Gears_wear_res"

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                Form3.BindingSource1.DataSource = table1
                Form3.DataGridView1.DataSource          =
Form3.BindingSource1
                Form3.DataGridView1.Columns(0).Visible    =
False
                Form3.DataGridView1.Columns(5).Visible    =
False
                Form3.DataGridView1.Columns(6).Visible    =
False
```

```
                Form3.DataGridView1.Columns(7).Visible    =
False
                Form3.DataGridView1.Columns(8).Visible    =
False
                Form3.DataGridView1.Columns(9).Visible    =
False
                Form3.DataGridView1.Columns(10).Visible   =
False
                Form3.DataGridView1.Refresh()

                ' MsgBox(table1.Columns.Count)

                Form3.Show()
                Me.Hide()


            Case "Fatique strength"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
Gears_fatique_str"

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                Form3.BindingSource1.DataSource = table1
                Form3.DataGridView1.DataSource            =
Form3.BindingSource1
                Form3.DataGridView1.Columns(0).Visible    =
False
                Form3.DataGridView1.Columns(5).Visible    =
False
                Form3.DataGridView1.Columns(6).Visible    =
False
                Form3.DataGridView1.Columns(7).Visible    =
False
                Form3.DataGridView1.Columns(8).Visible    =
False
                Form3.DataGridView1.Columns(9).Visible    =
False
                Form3.DataGridView1.Columns(10).Visible   =
False
                Form3.DataGridView1.Refresh()
```

```
                'MsgBox(table1.Columns.Count)

                Form3.Show()
                Me.Hide()


            Case "Impact strength"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText = "select * from Gears_impact_str"

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                Form3.BindingSource1.DataSource = table1
                Form3.DataGridView1.DataSource = Form3.BindingSource1
                Form3.DataGridView1.Columns(0).Visible = False
                Form3.DataGridView1.Columns(5).Visible = False
                Form3.DataGridView1.Columns(6).Visible = False
                Form3.DataGridView1.Columns(7).Visible = False
                Form3.DataGridView1.Columns(8).Visible = False
                Form3.DataGridView1.Columns(9).Visible = False
                Form3.DataGridView1.Columns(10).Visible = False
                Form3.DataGridView1.Refresh()

                Form3.Show()

                ' MsgBox(table1.Columns.Count)

                Me.Hide()


            Case "Cost"
```

```
                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
Gears_cost"

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                Form3.BindingSource1.DataSource = table1
                Form3.DataGridView1.DataSource          =
Form3.BindingSource1
                Form3.DataGridView1.Columns(0).Visible    =
False
                Form3.DataGridView1.Columns(5).Visible    =
False
                Form3.DataGridView1.Columns(6).Visible    =
False
                Form3.DataGridView1.Columns(7).Visible    =
False
                Form3.DataGridView1.Columns(8).Visible    =
False
                Form3.DataGridView1.Columns(9).Visible    =
False
                Form3.DataGridView1.Columns(10).Visible   =
False
                Form3.DataGridView1.Refresh()

                Form3.Show()
                Me.Hide()

        End Select
    End Sub

    Private  Sub  Form2_Load(ByVal  sender  As  System.Object,
ByVal e As System.EventArgs) Handles MyBase.Load

    End Sub

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        Form1.Show()

    End Sub
```

```
    Private Sub Button22_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub

    Private Sub Button6_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button6.Click

        TextBox1.Text = ""
        TextBox2.Text = ""
        TextBox3.Text = ""
        TextBox4.Text = ""

    End Sub
End Class

============================================================
====================================




Public Class Form3



    Private Sub DataGridView1_CellDoubleClick(ByVal sender
As Object, ByVal e As
System.Windows.Forms.DataGridViewCellEventArgs) Handles
DataGridView1.CellDoubleClick

        'Form4.DataGridView1.Rows.Clear()


        'get the chemical prop ----------------
        cmd1 = New OleDb.OleDbCommand
        cmd1.CommandType = CommandType.Text

        cmd1.CommandText = "select * from gears_chem_comp
where BS='" + BS_val + "' and AISI='" + AISI_val + "' and
DIN='" + DIN_val + "'"

        cmd1.Connection = con1_Gears
        DA1 = New OleDb.OleDbDataAdapter
        DA1.SelectCommand = cmd1
```

```
        qt_chemical.Rows.Clear()
        qt_chemical.Columns.Clear()

        DA1.Fill(qt_chemical)
        Form4.BindingSource1.DataSource = qt_chemical
        Form4.DataGridView1.DataSource                    =
Form4.BindingSource1
        Form4.DataGridView1.Columns(0).Visible = False
        Form4.DataGridView1.Columns(1).Visible = False
        Form4.DataGridView1.Columns(2).Visible = False
        Form4.DataGridView1.Columns(3).Visible = False
        'MsgBox(qt_chemical.Rows.Count)

        Form4.TabControl1.TabPages(0).Text    =    "chemical
properties"
        Form4.TextBox1.Text = BS_val
        Form4.TextBox2.Text = AISI_val
        Form4.TextBox3.Text = DIN_val
        Form4.Show()
        '----------------------------------------



        'get the mechanical prop (carburized) -------------
---
        Select Case Heat_treat_val

            Case "Carburized"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
gears_mech_Carburized where BS='" + BS_val + "' and AISI='"
+ AISI_val + "' and DIN='" + DIN_val + "'"

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_carburized.Rows.Clear()
                qt_carburized.Columns.Clear()

                DA1.Fill(qt_carburized)
                Form4.BindingSource2.DataSource           =
qt_carburized
                Form4.DataGridView2.DataSource            =
Form4.BindingSource2
                Form4.DataGridView2.Columns(0).Visible    =
False
```

```
                Form4.DataGridView2.Columns(1).Visible    =
False
                Form4.DataGridView2.Columns(2).Visible    =
False
                Form4.DataGridView2.Columns(3).Visible    =
False
                Form4.DataGridView2.Columns(11).Visible   =
False

                Form4.TabControl1.TabPages(1).Text        =
"Mechanical Properties as Carburizing treatment"
                Form4.TextBox1.Text = BS_val
                Form4.TextBox2.Text = AISI_val
                Form4.TextBox3.Text = DIN_val

                'Form4.TabControl1.TabPages(2).Hide()

                Form4.Show()
                Me.Hide()
                '----------------------------------------


            Case "Induction hardened"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
gears_mech_inducted where BS='" + BS_val + "' and AISI='" +
AISI_val + "' and DIN='" + DIN_val + "'"

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_inducted.Rows.Clear()
                qt_inducted.Columns.Clear()

                DA1.Fill(qt_inducted)
                Form4.BindingSource2.DataSource            =
qt_inducted
                Form4.DataGridView2.DataSource             =
Form4.BindingSource2
                Form4.DataGridView2.Columns(0).Visible    =
False
                Form4.DataGridView2.Columns(1).Visible    =
False
                Form4.DataGridView2.Columns(2).Visible    =
False
```

```
                Form4.DataGridView2.Columns(3).Visible    =
False
                Form4.DataGridView2.Columns(12).Visible   =
False

                Form4.TabControl1.TabPages(1).Text        =
"Mechanical Properties as Induction hardening"
                Form4.TextBox1.Text = BS_val
                Form4.TextBox2.Text = AISI_val
                Form4.TextBox3.Text = DIN_val

                'Form4.TabControl1.TabPages(2).Hide()

                Form4.Show()
                Me.Hide()

            Case "Nitrided"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
gears_mech_Nitrided where BS='" + BS_val + "' and AISI='" +
AISI_val + "' and DIN='" + DIN_val + "'"

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_nitrided.Rows.Clear()
                qt_nitrided.Columns.Clear()

                DA1.Fill(qt_nitrided)
                Form4.BindingSource2.DataSource           =
qt_nitrided
                Form4.DataGridView2.DataSource            =
Form4.BindingSource2
                Form4.DataGridView2.Columns(0).Visible    =
False
                Form4.DataGridView2.Columns(1).Visible    =
False
                Form4.DataGridView2.Columns(2).Visible    =
False
                Form4.DataGridView2.Columns(3).Visible    =
False
                Form4.DataGridView2.Columns(13).Visible   =
False

                Form4.TabControl1.TabPages(1).Text        =
"Mechanical Properties as Nitriding treatment"
```

```
                Form4.TextBox1.Text = BS_val
                Form4.TextBox2.Text = AISI_val
                Form4.TextBox3.Text = DIN_val


                'Form4.BindingSource3.DataSource          =
qt_nitrided
                'Form4.DataGridView3.DataSource           =
Form4.BindingSource3
                'Form4.DataGridView3.Columns(0).Visible   =
False
                'Form4.DataGridView3.Columns(1).Visible   =
False
                'Form4.DataGridView3.Columns(2).Visible   =
False
                'Form4.DataGridView3.Columns(3).Visible   =
False

                'Form4.DataGridView3.Columns(6).Visible   =
False
                'Form4.DataGridView3.Columns(7).Visible   =
False
                'Form4.DataGridView3.Columns(8).Visible   =
False
                'Form4.DataGridView3.Columns(9).Visible   =
False
                'Form4.DataGridView3.Columns(10).Visible  =
False
                'Form4.DataGridView3.Columns(11).Visible  =
False
                'Form4.DataGridView3.Columns(12).Visible  =
False
                'Form4.DataGridView3.Columns(13).Visible  =
False

                'Form4.TabControl1.TabPages(2).Text = "Heat
treatment"
                'Form4.DataGridView3.Columns(4).Width = 150
                'Form4.DataGridView3.Columns(5).Width = 150

                'Form4.TabControl1.TabPages(2).Show()

                Form4.Show()
                Me.Hide()

            Case Else '"H & T at 205"

                'get the heat degree
                Dim pos1 As Integer
```

```
                Dim Heat_deg As String
                pos1 = Heat_treat_val.LastIndexOf(" ")
                Heat_deg                                  =
Trim(Heat_treat_val.Substring(pos1))
                If     Not     IsNumeric(Heat_deg)     Then
MsgBox("error in heat degree")


                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
gears_mech_TH  where  BS='" + BS_val + "' and AISI='" +
AISI_val  +  "'  and  DIN='"  +  DIN_val  +  "'  and  [Tempering
temp]=" & CSng(Heat_deg)

                cmd1.Connection = con1_Gears
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_TH.Rows.Clear()
                qt_TH.Columns.Clear()

                DA1.Fill(qt_TH)
                Form4.BindingSource2.DataSource = qt_TH
                Form4.DataGridView2.DataSource            =
Form4.BindingSource2
                Form4.DataGridView2.Columns(0).Visible    =
False
                Form4.DataGridView2.Columns(1).Visible    =
False
                Form4.DataGridView2.Columns(2).Visible    =
False
                Form4.DataGridView2.Columns(3).Visible    =
False
                Form4.DataGridView2.Columns(13).Visible   =
False

                Form4.TabControl1.TabPages(1).Text        =
"Mechanical Properties as Through hardening condition"
                Form4.TextBox1.Text = BS_val
                Form4.TextBox2.Text = AISI_val
                Form4.TextBox3.Text = DIN_val


                'Form4.BindingSource3.DataSource = qt_TH
                'Form4.DataGridView3.DataSource           =
Form4.BindingSource3
                'Form4.DataGridView3.Columns(0).Visible   =
False
```

```
                'Form4.DataGridView3.Columns(1).Visible   =
False
                'Form4.DataGridView3.Columns(2).Visible   =
False
                'Form4.DataGridView3.Columns(3).Visible   =
False

                'Form4.DataGridView3.Columns(6).Visible   =
False
                'Form4.DataGridView3.Columns(7).Visible   =
False
                'Form4.DataGridView3.Columns(8).Visible   =
False
                'Form4.DataGridView3.Columns(9).Visible   =
False
                'Form4.DataGridView3.Columns(10).Visible  =
False
                'Form4.DataGridView3.Columns(11).Visible  =
False
                'Form4.DataGridView3.Columns(12).Visible  =
False
                'Form4.DataGridView3.Columns(13).Visible  =
False

                'Form4.TabControl1.TabPages(2).Text = "Heat
treatment"
                'Form4.DataGridView3.Columns(4).Width = 150
                'Form4.DataGridView3.Columns(5).Width = 150

                'Form4.TabControl1.TabPages(2).Show()


                Form4.Show()
                Me.Hide()

        End Select

    End Sub

    Private Sub DataGridView1_SelectionChanged(ByVal sender
As   Object,   ByVal   e   As   System.EventArgs)   Handles
DataGridView1.SelectionChanged

        On Error GoTo 1

        If   DataGridView1.SelectedCells(0).RowIndex   >   -1
Then
```

```
            BS_val                                          =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("BS").Value.ToString
            AISI_val                                        =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("AISI").Value.ToString
            DIN_val                                         =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("DIN").Value.ToString
            Heat_treat_val                                  =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("Heat treatment Condition").Value.ToString
        End If

1:

    End Sub

    Private Sub DataGridView1_CellContentClick(ByVal sender
As        System.Object,        ByVal        e        As
System.Windows.Forms.DataGridViewCellEventArgs)     Handles
DataGridView1.CellContentClick

    End Sub

    Private  Sub  Form3_Load(ByVal  sender  As  System.Object,
ByVal e As System.EventArgs) Handles MyBase.Load

    End Sub

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        Form2.Show()
    End Sub

    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized
    End Sub
End Class

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Public Class Form4
```

```
        Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        Form3.Show()
    End Sub
    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub

    End Class
```

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```
Public Class shafts_main_frm

    Private    Sub    Button1_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button1.Click


        If   TextBox1.Text   =   "Wear   resistance"   Or
TextBox2.Text = "Wear resistance" Or TextBox3.Text = "Wear
resistance" Or TextBox4.Text = "Wear resistance" Then Exit
Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Wear resistance"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Wear resistance"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Wear resistance"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Wear resistance"
        End If




    End Sub

    Private    Sub    Button2_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button2.Click
```

```
        If TextBox1.Text = "Fatique strength" Or TextBox2.Text = "Fatique strength" Or TextBox3.Text = "Fatique strength" Or TextBox4.Text = "Fatique strength" Then Exit Sub


        If TextBox1.Text = "" Then
            TextBox1.Text = "Fatique strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Fatique strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Fatique strength"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Fatique strength"
        End If


    End Sub

    Private Sub Button3_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button3.Click


        If TextBox1.Text = "Yield strength" Or TextBox2.Text = "Yield strength" Or TextBox3.Text = "Yield strength" Or TextBox4.Text = "Yield strength" Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Yield strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Yield strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Yield strength"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Yield strength"
        End If


    End Sub

    Private Sub Button4_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button4.Click

        If TextBox1.Text = "Cost" Or TextBox2.Text = "Cost" Or TextBox3.Text = "Cost" Or TextBox4.Text = "Cost" Then Exit Sub
```

```
        If TextBox1.Text = "" Then
            TextBox1.Text = "Cost"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Cost"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Cost"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Cost"
        End If

    End Sub

    Private    Sub    Button6_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button6.Click

        TextBox1.Text = ""
        TextBox2.Text = ""
        TextBox3.Text = ""
        TextBox4.Text = ""

    End Sub

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        Form1.Show()

    End Sub

    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub

    Private    Sub    Button5_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button5.Click


        Select Case TextBox1.Text

            Case "Wear resistance"

                cmd1 = New OleDb.OleDbCommand
```

```
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
Shafts_wear_res"
                'cmd1.CommandText          =          "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Shafts
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                shafts_rank_frm.BindingSource1.DataSource =
table1
                shafts_rank_frm.DataGridView1.DataSource  =
shafts_rank_frm.BindingSource1

shafts_rank_frm.DataGridView1.Columns(0).Visible = False

shafts_rank_frm.DataGridView1.Columns(5).Visible = False

shafts_rank_frm.DataGridView1.Columns(6).Visible = False

shafts_rank_frm.DataGridView1.Columns(7).Visible = False

shafts_rank_frm.DataGridView1.Columns(8).Visible = False

shafts_rank_frm.DataGridView1.Columns(9).Visible = False

shafts_rank_frm.DataGridView1.Columns(10).Visible = False

                shafts_rank_frm.Show()
                Me.Hide()


            Case "Fatique strength"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
Shafts_fatique_str"
                'cmd1.CommandText          =          "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Shafts
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()
```

```
                DA1.Fill(table1)
                shafts_rank_frm.BindingSource1.DataSource =
table1
                shafts_rank_frm.DataGridView1.DataSource  =
shafts_rank_frm.BindingSource1

shafts_rank_frm.DataGridView1.Columns(0).Visible = False

shafts_rank_frm.DataGridView1.Columns(5).Visible = False

shafts_rank_frm.DataGridView1.Columns(6).Visible = False

shafts_rank_frm.DataGridView1.Columns(7).Visible = False

shafts_rank_frm.DataGridView1.Columns(8).Visible = False

shafts_rank_frm.DataGridView1.Columns(9).Visible = False

shafts_rank_frm.DataGridView1.Columns(10).Visible = False

                shafts_rank_frm.Show()
                Me.Hide()


            Case "Yield strength"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
Shafts_High_str"
                'cmd1.CommandText         =          "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Shafts
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                shafts_rank_frm.BindingSource1.DataSource =
table1
                shafts_rank_frm.DataGridView1.DataSource  =
shafts_rank_frm.BindingSource1

shafts_rank_frm.DataGridView1.Columns(0).Visible = False

shafts_rank_frm.DataGridView1.Columns(5).Visible = False

shafts_rank_frm.DataGridView1.Columns(6).Visible = False
```

```
shafts_rank_frm.DataGridView1.Columns(7).Visible = False

shafts_rank_frm.DataGridView1.Columns(8).Visible = False

shafts_rank_frm.DataGridView1.Columns(9).Visible = False

shafts_rank_frm.DataGridView1.Columns(10).Visible = False

                shafts_rank_frm.Show()
                Me.Hide()



            Case "Cost"


                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
Shafts_cost"
                'cmd1.CommandText          =          "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Shafts
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                shafts_rank_frm.BindingSource1.DataSource =
table1
                shafts_rank_frm.DataGridView1.DataSource  =
shafts_rank_frm.BindingSource1

shafts_rank_frm.DataGridView1.Columns(0).Visible = False

shafts_rank_frm.DataGridView1.Columns(5).Visible = False

shafts_rank_frm.DataGridView1.Columns(6).Visible = False

shafts_rank_frm.DataGridView1.Columns(7).Visible = False

shafts_rank_frm.DataGridView1.Columns(8).Visible = False

shafts_rank_frm.DataGridView1.Columns(9).Visible = False

shafts_rank_frm.DataGridView1.Columns(10).Visible = False
```

```
                shafts_rank_frm.Show()
                Me.Hide()


        End Select


    End Sub
End Class

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Public Class shafts_rank_frm

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button23.Click
        Me.Hide()
        shafts_main_frm.Show()


    End Sub

    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub

    Private Sub DataGridView1_CellContentClick(ByVal sender
As       System.Object,       ByVal       e       As
System.Windows.Forms.DataGridViewCellEventArgs)    Handles
DataGridView1.CellContentClick

    End Sub

    Private Sub DataGridView1_CellDoubleClick(ByVal sender
As       Object,       ByVal       e       As
System.Windows.Forms.DataGridViewCellEventArgs)    Handles
DataGridView1.CellDoubleClick



        'Form4.DataGridView1.Rows.Clear()


        'get the chemical prop ----------------
```

```
        cmd1 = New OleDb.OleDbCommand
        cmd1.CommandType = CommandType.Text

        cmd1.CommandText = "select * from Shafts_chem_comp
where BS='" + BS_val + "' and AISI='" + AISI_val + "' and
DIN='" + DIN_val + "'"

        cmd1.Connection = con1_Shafts
        DA1 = New OleDb.OleDbDataAdapter
        DA1.SelectCommand = cmd1
        qt_chemical.Rows.Clear()
        qt_chemical.Columns.Clear()

        DA1.Fill(qt_chemical)
        shafts_detail_frm.BindingSource1.DataSource       =
qt_chemical
        shafts_detail_frm.DataGridView1.DataSource        =
shafts_detail_frm.BindingSource1
        shafts_detail_frm.DataGridView1.Columns(0).Visible
= False
        shafts_detail_frm.DataGridView1.Columns(1).Visible
= False
        shafts_detail_frm.DataGridView1.Columns(2).Visible
= False
        shafts_detail_frm.DataGridView1.Columns(3).Visible
= False
        'MsgBox(qt_chemical.Rows.Count)

        shafts_detail_frm.TabControl1.TabPages(0).Text    =
"chemical properties"
        shafts_detail_frm.TextBox1.Text = BS_val
        shafts_detail_frm.TextBox2.Text = AISI_val
        shafts_detail_frm.TextBox3.Text = DIN_val
        shafts_detail_frm.Show()
        '-----------------------------------------




        'get the mechanical prop (carburized) -------------
---
        Select Case Heat_treat_val

            Case "Carburized", "carburized"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
```

```
                cmd1.CommandText = "select * from Shafts_mech_Carburized where BS='" + BS_val + "' and AISI='" + AISI_val + "' and DIN='" + DIN_val + "'"

                cmd1.Connection = con1_Shafts
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_carburized.Rows.Clear()
                qt_carburized.Columns.Clear()

                DA1.Fill(qt_carburized)
                shafts_detail_frm.BindingSource2.DataSource = qt_carburized
                shafts_detail_frm.DataGridView2.DataSource = shafts_detail_frm.BindingSource2

shafts_detail_frm.DataGridView2.Columns(0).Visible = False

shafts_detail_frm.DataGridView2.Columns(1).Visible = False

shafts_detail_frm.DataGridView2.Columns(2).Visible = False

shafts_detail_frm.DataGridView2.Columns(3).Visible = False

shafts_detail_frm.DataGridView2.Columns(11).Visible = False


shafts_detail_frm.TabControl1.TabPages(1).Text = "Mechanical Properties as Carburizing treatment"
                shafts_detail_frm.TextBox1.Text = BS_val
                shafts_detail_frm.TextBox2.Text = AISI_val
                shafts_detail_frm.TextBox3.Text = DIN_val
                shafts_detail_frm.Show()
                Me.Hide()
                '-----------------------------------------

                'Case "Induction hardened"

                '    cmd1 = New OleDb.OleDbCommand
                '    cmd1.CommandType = CommandType.Text

                '      cmd1.CommandText = "select * from gears_mech_inducted where BS='" + BS_val + "' and AISI='" + AISI_val + "' and DIN='" + DIN_val + "'"

                '    cmd1.Connection = con1_Gears
                '    DA1 = New OleDb.OleDbDataAdapter
                '    DA1.SelectCommand = cmd1
```

```
                '    qt_inducted.Rows.Clear()

                '    DA1.Fill(qt_inducted)
                '        Form4.BindingSource2.DataSource  =
qt_inducted
                '         Form4.DataGridView2.DataSource  =
Form4.BindingSource2
                '    Form4.DataGridView2.Columns(0).Visible
= False
                '    Form4.DataGridView2.Columns(1).Visible
= False
                '    Form4.DataGridView2.Columns(2).Visible
= False
                '    Form4.DataGridView2.Columns(3).Visible
= False

                '      Form4.TabControl1.TabPages(1).Text  =
"Mechanical Properties as Induction hardening"
                '    Form4.TextBox1.Text = BS_val
                '    Form4.TextBox2.Text = AISI_val
                '    Form4.TextBox3.Text = DIN_val
                '    Form4.Show()
                '    Me.Hide()

            Case "Nitrided"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
shafts_mech_Nitrided where BS='" + BS_val + "' and AISI='"
+ AISI_val + "' and DIN='" + DIN_val + "'"

                cmd1.Connection = con1_Shafts
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_nitrided.Rows.Clear()
                qt_nitrided.Columns.Clear()

                DA1.Fill(qt_nitrided)
                shafts_detail_frm.BindingSource2.DataSource
= qt_nitrided
                shafts_detail_frm.DataGridView2.DataSource
= shafts_detail_frm.BindingSource2

shafts_detail_frm.DataGridView2.Columns(0).Visible = False

shafts_detail_frm.DataGridView2.Columns(1).Visible = False
```

```
shafts_detail_frm.DataGridView2.Columns(2).Visible = False

shafts_detail_frm.DataGridView2.Columns(3).Visible = False

shafts_detail_frm.DataGridView2.Columns(13).Visible = False


shafts_detail_frm.TabControl1.TabPages(1).Text =
"Mechanical Properties as Nitriding treatment"
                shafts_detail_frm.TextBox1.Text = BS_val
                shafts_detail_frm.TextBox2.Text = AISI_val
                shafts_detail_frm.TextBox3.Text = DIN_val
                shafts_detail_frm.Show()
                Me.Hide()

            Case Else '"H & T at 205"

                'get the heat degree
                Dim pos1 As Integer
                Dim Heat_deg As String
                pos1 = Heat_treat_val.LastIndexOf(" ")
                Heat_deg =
Trim(Heat_treat_val.Substring(pos1))
                If Not IsNumeric(Heat_deg) Then
MsgBox("error in heat degree")


                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText = "select * from
shafts_mech_TH where BS='" + BS_val + "' and AISI='" +
AISI_val + "' and DIN='" + DIN_val + "' and [Tempering
temp]=" & CSng(Heat_deg)

                cmd1.Connection = con1_Shafts
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_TH.Rows.Clear()
                qt_TH.Columns.Clear()

                DA1.Fill(qt_TH)
                shafts_detail_frm.BindingSource2.DataSource
= qt_TH
                shafts_detail_frm.DataGridView2.DataSource
= shafts_detail_frm.BindingSource2

shafts_detail_frm.DataGridView2.Columns(0).Visible = False
```

```
shafts_detail_frm.DataGridView2.Columns(1).Visible = False

shafts_detail_frm.DataGridView2.Columns(2).Visible = False

shafts_detail_frm.DataGridView2.Columns(3).Visible = False

shafts_detail_frm.DataGridView2.Columns(13).Visible = False


shafts_detail_frm.TabControl1.TabPages(1).Text           =
"Mechanical Properties as Through hardening condition"
                shafts_detail_frm.TextBox1.Text = BS_val
                shafts_detail_frm.TextBox2.Text = AISI_val
                shafts_detail_frm.TextBox3.Text = DIN_val
                shafts_detail_frm.Show()
                Me.Hide()

        End Select



    End Sub

    Private Sub DataGridView1_SelectionChanged(ByVal sender
As   Object,   ByVal   e   As   System.EventArgs)   Handles
DataGridView1.SelectionChanged

        On Error GoTo 1

        BS_val                                                =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("BS").Value.ToString
        AISI_val                                              =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("AISI").Value.ToString
        DIN_val                                               =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("DIN").Value.ToString
        Heat_treat_val                                        =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("Heat treatment Condition").Value.ToString

1:

    End Sub
```

```
    Private   Sub   shafts_rank_frm_Load(ByVal   sender   As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
MyBase.Load

    End Sub
End Class
============================================================
==================================


Public Class shafts_detail_frm

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        shafts_rank_frm.Show()
    End Sub

    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized
    End Sub
End Class

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Public Class springs_detail_frm

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        springs_rank_frm.Show()
    End Sub

    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub
End Class
```

```
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Public Class springs_main_frm

    Private Sub Button23_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button23.Click
        Me.Hide()
        Form1.Show()
    End Sub

    Private Sub Button22_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub

    Private Sub Button6_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button6.Click

        TextBox1.Text = ""
        TextBox2.Text = ""
        TextBox3.Text = ""
        TextBox4.Text = ""


    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button1.Click


        If TextBox1.Text = "Ductile" Or TextBox2.Text = "Ductile" Or TextBox3.Text = "Ductile" Or TextBox4.Text = "Ductile" Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Ductile"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Ductile"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Ductile"

        ElseIf TextBox4.Text = "" Then
```

```
            TextBox4.Text = "Ductile"

        End If

    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button2.Click

        If TextBox1.Text = "Yield strength" Or TextBox2.Text = "Yield strength" Or TextBox3.Text = "Yield strength" Or TextBox4.Text = "Yield strength" Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Yield strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Yield strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Yield strength"

        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Yield strength"

        End If

    End Sub

    Private Sub Button4_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button4.Click


        If TextBox1.Text = "Cost" Or TextBox2.Text = "Cost" Or TextBox3.Text = "Cost" Or TextBox4.Text = "Cost" Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Cost"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Cost"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Cost"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Cost"


        End If
```

```
    End Sub

    Private Sub Button5_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button5.Click


        Select Case TextBox1.Text

            Case "Ductile"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText = "select * from
springs_ductile"
                'cmd1.CommandText = "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Springs
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                springs_rank_frm.BindingSource1.DataSource
= table1
                springs_rank_frm.DataGridView1.DataSource =
springs_rank_frm.BindingSource1

springs_rank_frm.DataGridView1.Columns(0).Visible = False

springs_rank_frm.DataGridView1.Columns(5).Visible = False

springs_rank_frm.DataGridView1.Columns(6).Visible = False

springs_rank_frm.DataGridView1.Columns(7).Visible = False

springs_rank_frm.DataGridView1.Columns(8).Visible = False

springs_rank_frm.DataGridView1.Columns(9).Visible = False

springs_rank_frm.DataGridView1.Columns(10).Visible = False

                springs_rank_frm.Show()
                Me.Hide()


            Case "Yield strength"
```

```
                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
springs_high_strength"
                'cmd1.CommandText         =         "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Springs
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                springs_rank_frm.BindingSource1.DataSource
= table1
                springs_rank_frm.DataGridView1.DataSource =
springs_rank_frm.BindingSource1

springs_rank_frm.DataGridView1.Columns(0).Visible = False

springs_rank_frm.DataGridView1.Columns(5).Visible = False

springs_rank_frm.DataGridView1.Columns(6).Visible = False

springs_rank_frm.DataGridView1.Columns(7).Visible = False

springs_rank_frm.DataGridView1.Columns(8).Visible = False

springs_rank_frm.DataGridView1.Columns(9).Visible = False

springs_rank_frm.DataGridView1.Columns(10).Visible = False

                springs_rank_frm.Show()
                Me.Hide()


            Case "Fatigue strength"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
High_fatigue_strenght"
                'cmd1.CommandText         =         "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Springs

                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
```

```
                table1.Columns.Clear()

                DA1.Fill(table1)
                springs_rank_frm.BindingSource1.DataSource
= table1
                springs_rank_frm.DataGridView1.DataSource =
springs_rank_frm.BindingSource1

springs_rank_frm.DataGridView1.Columns(0).Visible = False

springs_rank_frm.DataGridView1.Columns(5).Visible = False

springs_rank_frm.DataGridView1.Columns(6).Visible = False

springs_rank_frm.DataGridView1.Columns(7).Visible = False

springs_rank_frm.DataGridView1.Columns(8).Visible = False

springs_rank_frm.DataGridView1.Columns(9).Visible = False

springs_rank_frm.DataGridView1.Columns(10).Visible = False

                springs_rank_frm.Show()
                Me.Hide()



            Case "Cost"


                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
springs_cost"
                'cmd1.CommandText         =         "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Springs

                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)
                springs_rank_frm.BindingSource1.DataSource
= table1
                springs_rank_frm.DataGridView1.DataSource =
springs_rank_frm.BindingSource1
```

```
springs_rank_frm.DataGridView1.Columns(0).Visible = False

springs_rank_frm.DataGridView1.Columns(5).Visible = False

springs_rank_frm.DataGridView1.Columns(6).Visible = False

springs_rank_frm.DataGridView1.Columns(7).Visible = False

springs_rank_frm.DataGridView1.Columns(8).Visible = False

springs_rank_frm.DataGridView1.Columns(9).Visible = False

springs_rank_frm.DataGridView1.Columns(10).Visible = False

                springs_rank_frm.Show()
                Me.Hide()


        End Select




    End Sub

    Private Sub springs_main_frm_Load(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
MyBase.Load

    End Sub

    Private Sub Button3_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button3.Click

        If TextBox1.Text = "Fatigue strength" Or
TextBox2.Text = "Fatigue strength" Or TextBox3.Text =
"Fatigue strength" Or TextBox4.Text = "Fatigue strength"
Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Fatigue strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Fatigue strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Fatigue strength"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Fatigue strength"
```

```
        End If


    End Sub
End Class

============================================================
===========================

Public Class springs_rank_frm

    Private Sub Button23_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button23.Click
        Me.Hide()
        springs_main_frm.Show()
    End Sub

    Private Sub Button22_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized
    End Sub

    Private Sub DataGridView1_CellContentClick(ByVal sender
As System.Object, ByVal e As
System.Windows.Forms.DataGridViewCellEventArgs) Handles
DataGridView1.CellContentClick

    End Sub

    Private Sub DataGridView1_CellDoubleClick(ByVal sender
As Object, ByVal e As
System.Windows.Forms.DataGridViewCellEventArgs) Handles
DataGridView1.CellDoubleClick


        'Form4.DataGridView1.Rows.Clear()


        'get the chemical prop ----------------
        cmd1 = New OleDb.OleDbCommand
        cmd1.CommandType = CommandType.Text

        cmd1.CommandText = "select * from springs_chem_prop
where BS='" + BS_val + "' and AISI='" + AISI_val + "' and
DIN='" + DIN_val + "'"
```

```
        cmd1.Connection = con1_Springs
        DA1 = New OleDb.OleDbDataAdapter
        DA1.SelectCommand = cmd1
        qt_chemical.Rows.Clear()
        qt_chemical.Columns.Clear()

        DA1.Fill(qt_chemical)
        springs_detail_frm.BindingSource1.DataSource      =
qt_chemical
        springs_detail_frm.DataGridView1.DataSource       =
springs_detail_frm.BindingSource1
        springs_detail_frm.DataGridView1.Columns(0).Visible
= False
        springs_detail_frm.DataGridView1.Columns(1).Visible
= False
        springs_detail_frm.DataGridView1.Columns(2).Visible
= False
        springs_detail_frm.DataGridView1.Columns(3).Visible
= False
        'MsgBox(qt_chemical.Rows.Count)

        springs_detail_frm.TabControl1.TabPages(0).Text   =
"chemical properties"
        springs_detail_frm.TextBox1.Text = BS_val
        springs_detail_frm.TextBox2.Text = AISI_val
        springs_detail_frm.TextBox3.Text = DIN_val
        springs_detail_frm.Show()
        '----------------------------------------

        'get the mechanical prop (carburized) -------------
---
        Select Case Heat_treat_val

            'Case "Carburized", "carburized"

            '    cmd1 = New OleDb.OleDbCommand
            '    cmd1.CommandType = CommandType.Text

            '        cmd1.CommandText   =   "select   *   from
Shafts_mech_Carburized  where  BS='"  +  BS_val  +  "'  and
AISI='" + AISI_val + "' and DIN='" + DIN_val + "'"

            '    cmd1.Connection = con1_Shafts
            '    DA1 = New OleDb.OleDbDataAdapter
            '    DA1.SelectCommand = cmd1
            '    qt_carburized.Rows.Clear()

            '    DA1.Fill(qt_carburized)
```

```
            '
shafts_detail_frm.BindingSource2.DataSource = qt_carburized
            '    shafts_detail_frm.DataGridView2.DataSource
= shafts_detail_frm.BindingSource2
            '
shafts_detail_frm.DataGridView2.Columns(0).Visible = False
            '
shafts_detail_frm.DataGridView2.Columns(1).Visible = False
            '
shafts_detail_frm.DataGridView2.Columns(2).Visible = False
            '
shafts_detail_frm.DataGridView2.Columns(3).Visible = False

            '
shafts_detail_frm.TabControl1.TabPages(1).Text            =
"Mechanical Properties as Carburizing treatment"
            '    shafts_detail_frm.TextBox1.Text = BS_val
            '    shafts_detail_frm.TextBox2.Text = AISI_val
            '    shafts_detail_frm.TextBox3.Text = DIN_val
            '    shafts_detail_frm.Show()
            '    Me.Hide()
            '----------------------------------------


            'Case "Induction hardened"

            '    cmd1 = New OleDb.OleDbCommand
            '    cmd1.CommandType = CommandType.Text

            '        cmd1.CommandText  =  "select  *  from
gears_mech_inducted where BS='" + BS_val + "' and AISI='" +
AISI_val + "' and DIN='" + DIN_val + "'"

            '    cmd1.Connection = con1_Gears
            '    DA1 = New OleDb.OleDbDataAdapter
            '    DA1.SelectCommand = cmd1
            '    qt_inducted.Rows.Clear()

            '    DA1.Fill(qt_inducted)
            '          Form4.BindingSource2.DataSource   =
qt_inducted
            '           Form4.DataGridView2.DataSource   =
Form4.BindingSource2
            '      Form4.DataGridView2.Columns(0).Visible  =
False
            '      Form4.DataGridView2.Columns(1).Visible  =
False
            '      Form4.DataGridView2.Columns(2).Visible  =
False
```

```
            '      Form4.DataGridView2.Columns(3).Visible  =
False

            '         Form4.TabControl1.TabPages(1).Text  =
"Mechanical Properties as Induction hardening"
            '    Form4.TextBox1.Text = BS_val
            '    Form4.TextBox2.Text = AISI_val
            '    Form4.TextBox3.Text = DIN_val
            '    Form4.Show()
            '    Me.Hide()

            Case  "Nitrided"  'theres  no  nitrided  in  the
table

                'cmd1 = New OleDb.OleDbCommand
                'cmd1.CommandType = CommandType.Text

                'cmd1.CommandText   =   "select   *   from
shafts_mech_Nitrided where BS='" + BS_val + "' and AISI='"
+ AISI_val + "' and DIN='" + DIN_val + "'"

                'cmd1.Connection = con1_Shafts
                'DA1 = New OleDb.OleDbDataAdapter
                'DA1.SelectCommand = cmd1
                'qt_nitrided.Rows.Clear()

                'DA1.Fill(qt_nitrided)

'shafts_detail_frm.BindingSource2.DataSource = qt_nitrided
                'shafts_detail_frm.DataGridView2.DataSource
= shafts_detail_frm.BindingSource2

'shafts_detail_frm.DataGridView2.Columns(0).Visible = False

'shafts_detail_frm.DataGridView2.Columns(1).Visible = False

'shafts_detail_frm.DataGridView2.Columns(2).Visible = False

'shafts_detail_frm.DataGridView2.Columns(3).Visible = False


'shafts_detail_frm.TabControl1.TabPages(1).Text          =
"Mechanical Properties as Nitriding treatment"
                'shafts_detail_frm.TextBox1.Text = BS_val
                'shafts_detail_frm.TextBox2.Text = AISI_val
                'shafts_detail_frm.TextBox3.Text = DIN_val
                'shafts_detail_frm.Show()
                'Me.Hide()
```

```
            Case Else '"H & T at 205"

                'get the heat degree
                Dim pos1 As Integer
                Dim Heat_deg As String
                pos1 = Heat_treat_val.LastIndexOf(" ")
                Heat_deg                                   =
Trim(Heat_treat_val.Substring(pos1))
                If     Not     IsNumeric(Heat_deg)     Then
MsgBox("error in heat degree")


                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
springs_mech_prop where BS='" + BS_val + "' and AISI='" +
AISI_val  +  "'  and  DIN='"  +  DIN_val  +  "'  and  [Tempering
temp]=" & CSng(Heat_deg)

                cmd1.Connection = con1_Springs

                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_TH.Rows.Clear()
                qt_TH.Columns.Clear()

                DA1.Fill(qt_TH)

springs_detail_frm.BindingSource2.DataSource = qt_TH
                springs_detail_frm.DataGridView2.DataSource
= springs_detail_frm.BindingSource2

springs_detail_frm.DataGridView2.Columns(0).Visible = False

springs_detail_frm.DataGridView2.Columns(1).Visible = False

springs_detail_frm.DataGridView2.Columns(2).Visible = False

springs_detail_frm.DataGridView2.Columns(3).Visible = False

springs_detail_frm.DataGridView2.Columns(12).Visible      =
False


springs_detail_frm.TabControl1.TabPages(1).Text           =
"Mechanical Properties for Spring Steels"
                springs_detail_frm.TextBox1.Text = BS_val
                springs_detail_frm.TextBox2.Text = AISI_val
```

```
                springs_detail_frm.TextBox3.Text = DIN_val
                springs_detail_frm.Show()
                Me.Hide()

        End Select



    End Sub

    Private Sub DataGridView1_SelectionChanged(ByVal sender
As    Object,    ByVal    e    As    System.EventArgs)    Handles
DataGridView1.SelectionChanged


        On Error GoTo 1

        BS_val                                                  =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("BS").Value.ToString
        AISI_val                                                =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("AISI").Value.ToString
        DIN_val                                                 =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("DIN").Value.ToString
        Heat_treat_val                                          =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("Heat treatment Condition").Value.ToString

1:



    End Sub
End Class

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Public Class fasteners_detail_frm

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        fasteners_rank_frm.Show()
    End Sub
```

```
    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized
    End Sub

    Private Sub DataGridView1_CellContentClick(ByVal sender
As         System.Object,          ByVal          e          As
System.Windows.Forms.DataGridViewCellEventArgs)     Handles
DataGridView1.CellContentClick

    End Sub
End Class

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Public Class fasteners_main_frm

    Private    Sub    Button1_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button1.Click

        If  TextBox1.Text  =  "Hardness"  Or  TextBox2.Text  =
"Hardness" Or TextBox3.Text = "Hardness" Or TextBox4.Text =
"Hardness" Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Hardness"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Hardness"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Hardness"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Hardness"
        End If

    End Sub

    Private    Sub    Button2_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button2.Click


        If  TextBox1.Text  =  "Shear  fatique  strength"  Or
TextBox2.Text = "Shear fatique strength" Or TextBox3.Text =
"Shear fatique strength" Or TextBox4.Text = "Shear fatique
strength" Then Exit Sub
```

```
        If TextBox1.Text = "" Then
            TextBox1.Text = "Shear fatique strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Shear fatique strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Shear fatique strength"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Shear fatique strength"
        End If

    End Sub

    Private Sub Button3_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button3.Click

        If TextBox1.Text = "Tensile strength" Or
TextBox2.Text = "Tensile strength" Or TextBox3.Text =
"Tensile strength" Or TextBox4.Text = "Tensile strength"
Then Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Tensile strength"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Tensile strength"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Tensile strength"
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Tensile strength"
        End If

    End Sub

    Private Sub Button4_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
Button4.Click


        If TextBox1.Text = "Cost" Or TextBox2.Text = "Cost"
Or TextBox3.Text = "Cost" Or TextBox4.Text = "Cost" Then
Exit Sub

        If TextBox1.Text = "" Then
            TextBox1.Text = "Cost"
        ElseIf TextBox2.Text = "" Then
            TextBox2.Text = "Cost"
        ElseIf TextBox3.Text = "" Then
            TextBox3.Text = "Cost"
```

```
        ElseIf TextBox4.Text = "" Then
            TextBox4.Text = "Cost"
        End If

    End Sub

    Private Sub Button6_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button6.Click

        TextBox1.Text = ""
        TextBox2.Text = ""
        TextBox3.Text = ""
        TextBox4.Text = ""

    End Sub

    Private Sub Button5_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button5.Click

        Select Case TextBox1.Text

            Case "Hardness"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText = "select * from fasteners_hardness"
                'cmd1.CommandText = "select BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Fasteners
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()

                DA1.Fill(table1)

fasteners_rank_frm.BindingSource1.DataSource = table1
                fasteners_rank_frm.DataGridView1.DataSource = fasteners_rank_frm.BindingSource1

fasteners_rank_frm.DataGridView1.Columns(0).Visible = False

fasteners_rank_frm.DataGridView1.Columns(5).Visible = False

fasteners_rank_frm.DataGridView1.Columns(6).Visible = False
```

```
fasteners_rank_frm.DataGridView1.Columns(7).Visible = False

fasteners_rank_frm.DataGridView1.Columns(8).Visible = False

fasteners_rank_frm.DataGridView1.Columns(9).Visible = False

fasteners_rank_frm.DataGridView1.Columns(10).Visible      =
False

                fasteners_rank_frm.Show()
                Me.Hide()


            Case "Shear fatique strength"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
fasteners_shear_fatique"
                'cmd1.CommandText         =         "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Fasteners
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()


                DA1.Fill(table1)

fasteners_rank_frm.BindingSource1.DataSource = table1
                fasteners_rank_frm.DataGridView1.DataSource
= fasteners_rank_frm.BindingSource1

fasteners_rank_frm.DataGridView1.Columns(0).Visible = False

fasteners_rank_frm.DataGridView1.Columns(5).Visible = False

fasteners_rank_frm.DataGridView1.Columns(6).Visible = False

fasteners_rank_frm.DataGridView1.Columns(7).Visible = False

fasteners_rank_frm.DataGridView1.Columns(8).Visible = False

fasteners_rank_frm.DataGridView1.Columns(9).Visible = False

fasteners_rank_frm.DataGridView1.Columns(10).Visible      =
False
```

```
                fasteners_rank_frm.Show()
                Me.Hide()


            Case "Tensile strength"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
fasteners_strength"
                'cmd1.CommandText         =         "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Fasteners
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()


                DA1.Fill(table1)

fasteners_rank_frm.BindingSource1.DataSource = table1
                fasteners_rank_frm.DataGridView1.DataSource
= fasteners_rank_frm.BindingSource1

fasteners_rank_frm.DataGridView1.Columns(0).Visible = False

fasteners_rank_frm.DataGridView1.Columns(5).Visible = False

fasteners_rank_frm.DataGridView1.Columns(6).Visible = False

fasteners_rank_frm.DataGridView1.Columns(7).Visible = False

fasteners_rank_frm.DataGridView1.Columns(8).Visible = False

fasteners_rank_frm.DataGridView1.Columns(9).Visible = False

fasteners_rank_frm.DataGridView1.Columns(10).Visible      =
False

                fasteners_rank_frm.Show()
                Me.Hide()



            Case "Cost"
```

```
                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text
                cmd1.CommandText    =    "select    *    from
fasteners_cost"
                'cmd1.CommandText         =         "select
BS,AISI,DIN,Condition,Ranking from Gears_wear_res"
                cmd1.Connection = con1_Fasteners
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                table1.Rows.Clear()
                table1.Columns.Clear()


                DA1.Fill(table1)

fasteners_rank_frm.BindingSource1.DataSource = table1
                fasteners_rank_frm.DataGridView1.DataSource
= fasteners_rank_frm.BindingSource1

fasteners_rank_frm.DataGridView1.Columns(0).Visible = False

fasteners_rank_frm.DataGridView1.Columns(5).Visible = False

fasteners_rank_frm.DataGridView1.Columns(6).Visible = False

fasteners_rank_frm.DataGridView1.Columns(7).Visible = False

fasteners_rank_frm.DataGridView1.Columns(8).Visible = False

fasteners_rank_frm.DataGridView1.Columns(9).Visible = False

fasteners_rank_frm.DataGridView1.Columns(10).Visible      =
False

                fasteners_rank_frm.Show()
                Me.Hide()

        End Select

    End Sub

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,   ByVal   e   As   System.EventArgs)   Handles
Button23.Click
        Me.Hide()
        Form1.Show()
    End Sub
```

```
    Private Sub Button22_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub
End Class
```

==

```
Public Class fasteners_rank_frm

    Private Sub DataGridView1_CellContentClick(ByVal sender As System.Object, ByVal e As System.Windows.Forms.DataGridViewCellEventArgs) Handles DataGridView1.CellContentClick

    End Sub

    Private Sub DataGridView1_CellDoubleClick(ByVal sender As Object, ByVal e As System.Windows.Forms.DataGridViewCellEventArgs) Handles DataGridView1.CellDoubleClick


        'Form4.DataGridView1.Rows.Clear()


        'get the chemical prop ----------------
        cmd1 = New OleDb.OleDbCommand
        cmd1.CommandType = CommandType.Text

        cmd1.CommandText = "select * from fasteners_chem_comp where BS='" + BS_val + "' and AISI='" + AISI_val + "' and DIN='" + DIN_val + "'"

        cmd1.Connection = con1_Fasteners
        DA1 = New OleDb.OleDbDataAdapter
        DA1.SelectCommand = cmd1
        qt_chemical.Rows.Clear()
        qt_chemical.Columns.Clear()

        DA1.Fill(qt_chemical)
        fasteners_detail_frm.BindingSource1.DataSource = qt_chemical
        fasteners_detail_frm.DataGridView1.DataSource = fasteners_detail_frm.BindingSource1
```

```
fasteners_detail_frm.DataGridView1.Columns(0).Visible     =
False

fasteners_detail_frm.DataGridView1.Columns(1).Visible     =
False

fasteners_detail_frm.DataGridView1.Columns(2).Visible     =
False

fasteners_detail_frm.DataGridView1.Columns(3).Visible     =
False

        'MsgBox(qt_chemical.Rows.Count)

        fasteners_detail_frm.TabControl1.TabPages(0).Text =
"chemical properties"
        fasteners_detail_frm.TextBox1.Text = BS_val
        fasteners_detail_frm.TextBox2.Text = AISI_val
        fasteners_detail_frm.TextBox3.Text = DIN_val
        fasteners_detail_frm.Show()
        '----------------------------------------

        'get the mechanical prop (carburized) -------------
---
        Select Case Heat_treat_val

            Case "Carburized", "carburized"

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
fasteners_mech_Carburized  where  BS='" + BS_val +  "'  and
AISI='" + AISI_val + "' and DIN='" + DIN_val + "'"

                cmd1.Connection = con1_Fasteners
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_carburized.Rows.Clear()
                qt_carburized.Columns.Clear()


                DA1.Fill(qt_carburized)

fasteners_detail_frm.BindingSource2.DataSource            =
qt_carburized
```

```
fasteners_detail_frm.DataGridView2.DataSource =
fasteners_detail_frm.BindingSource2

fasteners_detail_frm.DataGridView2.Columns(0).Visible =
False

fasteners_detail_frm.DataGridView2.Columns(1).Visible =
False

fasteners_detail_frm.DataGridView2.Columns(2).Visible =
False

fasteners_detail_frm.DataGridView2.Columns(3).Visible =
False

fasteners_detail_frm.DataGridView2.Columns(11).Visible =
False


fasteners_detail_frm.TabControl1.TabPages(1).Text =
"Mechanical Properties as Carburizing treatment"
                fasteners_detail_frm.TextBox1.Text = BS_val
                fasteners_detail_frm.TextBox2.Text =
AISI_val
                fasteners_detail_frm.TextBox3.Text =
DIN_val
                fasteners_detail_frm.Show()
                Me.Hide()
                '-----------------------------------------


                'Case "Induction hardened"

                '    cmd1 = New OleDb.OleDbCommand
                '    cmd1.CommandType = CommandType.Text

                '      cmd1.CommandText = "select * from
gears_mech_inducted where BS='" + BS_val + "' and AISI='" +
AISI_val + "' and DIN='" + DIN_val + "'"

                '    cmd1.Connection = con1_Gears
                '    DA1 = New OleDb.OleDbDataAdapter
                '    DA1.SelectCommand = cmd1
                '    qt_inducted.Rows.Clear()

                '    DA1.Fill(qt_inducted)
                '        Form4.BindingSource2.DataSource =
qt_inducted
```

```
                '        Form4.DataGridView2.DataSource  =
Form4.BindingSource2
                '    Form4.DataGridView2.Columns(0).Visible
= False
                '    Form4.DataGridView2.Columns(1).Visible
= False
                '    Form4.DataGridView2.Columns(2).Visible
= False
                '    Form4.DataGridView2.Columns(3).Visible
= False

                '      Form4.TabControl1.TabPages(1).Text  =
"Mechanical Properties as Induction hardening"
                '    Form4.TextBox1.Text = BS_val
                '    Form4.TextBox2.Text = AISI_val
                '    Form4.TextBox3.Text = DIN_val
                '    Form4.Show()
                '    Me.Hide()

            Case "Hot Rolled" 'i used qt_nitrided instead
of making a new query for 'hot rolled'

                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
fasteners_mech_hot_rolled where BS='" + BS_val + "' and
AISI='" + AISI_val + "' and DIN='" + DIN_val + "'"

                cmd1.Connection = con1_Fasteners
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_nitrided.Rows.Clear()
                qt_nitrided.Columns.Clear()

                DA1.Fill(qt_nitrided)

fasteners_detail_frm.BindingSource2.DataSource            =
qt_nitrided

fasteners_detail_frm.DataGridView2.DataSource             =
fasteners_detail_frm.BindingSource2

fasteners_detail_frm.DataGridView2.Columns(0).Visible     =
False

fasteners_detail_frm.DataGridView2.Columns(1).Visible     =
False
```

```
fasteners_detail_frm.DataGridView2.Columns(2).Visible     =
False

fasteners_detail_frm.DataGridView2.Columns(3).Visible     =
False

fasteners_detail_frm.DataGridView2.Columns(11).Visible    =
False


fasteners_detail_frm.TabControl1.TabPages(1).Text         =
"Mechanical Properties as Hot Rolled treatment"
                fasteners_detail_frm.TextBox1.Text = BS_val
                fasteners_detail_frm.TextBox2.Text         =
AISI_val
                fasteners_detail_frm.TextBox3.Text         =
DIN_val
                fasteners_detail_frm.Show()
                Me.Hide()


            Case Else '"H & T at 205"

                'get the heat degree
                Dim pos1 As Integer
                Dim Heat_deg As String
                pos1 = Heat_treat_val.LastIndexOf(" ")
                Heat_deg                                   =
Trim(Heat_treat_val.Substring(pos1))
                If     Not     IsNumeric(Heat_deg)     Then
MsgBox("error in heat degree") : Exit Sub


                cmd1 = New OleDb.OleDbCommand
                cmd1.CommandType = CommandType.Text

                cmd1.CommandText    =    "select    *    from
fasteners_mech_TH where BS='" + BS_val + "' and AISI='" +
AISI_val + "' and DIN='" + DIN_val + "' and [Tempering
temp]=" & CSng(Heat_deg)

                cmd1.Connection = con1_Fasteners
                DA1 = New OleDb.OleDbDataAdapter
                DA1.SelectCommand = cmd1
                qt_TH.Rows.Clear()
                qt_TH.Columns.Clear()

                DA1.Fill(qt_TH)
```

```
fasteners_detail_frm.BindingSource2.DataSource = qt_TH

fasteners_detail_frm.DataGridView2.DataSource           =
fasteners_detail_frm.BindingSource2

fasteners_detail_frm.DataGridView2.Columns(0).Visible     =
False

fasteners_detail_frm.DataGridView2.Columns(1).Visible     =
False

fasteners_detail_frm.DataGridView2.Columns(2).Visible     =
False

fasteners_detail_frm.DataGridView2.Columns(3).Visible     =
False

fasteners_detail_frm.DataGridView2.Columns(13).Visible    =
False


fasteners_detail_frm.TabControl1.TabPages(1).Text        =
"Mechanical Properties as Through hardening condition"
                fasteners_detail_frm.TextBox1.Text = BS_val
                fasteners_detail_frm.TextBox2.Text        =
AISI_val
                fasteners_detail_frm.TextBox3.Text        =
DIN_val
                fasteners_detail_frm.Show()
                Me.Hide()

        End Select


    End Sub

    Private Sub DataGridView1_SelectionChanged(ByVal sender
As   Object,   ByVal   e   As   System.EventArgs)   Handles
DataGridView1.SelectionChanged


        On Error GoTo 1

        BS_val                                                 =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("BS").Value.ToString
```

```
        AISI_val                                                =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("AISI").Value.ToString
        DIN_val                                                 =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("DIN").Value.ToString
        Heat_treat_val                                          =
DataGridView1.Rows(DataGridView1.SelectedCells(0).RowIndex)
.Cells("Heat treatment Condition").Value.ToString
        'MsgBox(Heat_treat_val)

1:

    End Sub

    Private    Sub    Button23_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button23.Click

        Me.Hide()
        fasteners_main_frm.Show()

    End Sub

    Private    Sub    Button22_Click(ByVal    sender    As
System.Object,  ByVal  e  As  System.EventArgs)  Handles
Button22.Click
        Me.WindowState = FormWindowState.Minimized

    End Sub
End Class

===========================================================
===========
```